UCRL-CONF-217301

LAWRENCE LIVERMORE NATIONAL LABORATORY

Present Status and First Experiments on the National Ignition Facility

O. L. Landen

November 23, 2005

Japanese Society for Plasma Science and Nuclear Fusion Research
Tokyo, Japan
December 1, 2005 through December 2, 2005

Present Status and First Experiments on the National Ignition Facility*

Presented to:

Japanese Society for Plasma Science and Nuclear Fusion Research

Tokyo, Japan

December 1, 2005

Otto L. Landen

Associate Program Leader

Ignition Physics Experiments

Lawrence Livermore National Laboratory

Los Alamos NATIONAL LABORATORY · AWE · GENERAL ATOMICS · Bechtel Nevada · Sandia National Laboratories · UR LLE · cea

*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

There are two principal approaches to compression in Inertial Confinement Fusion

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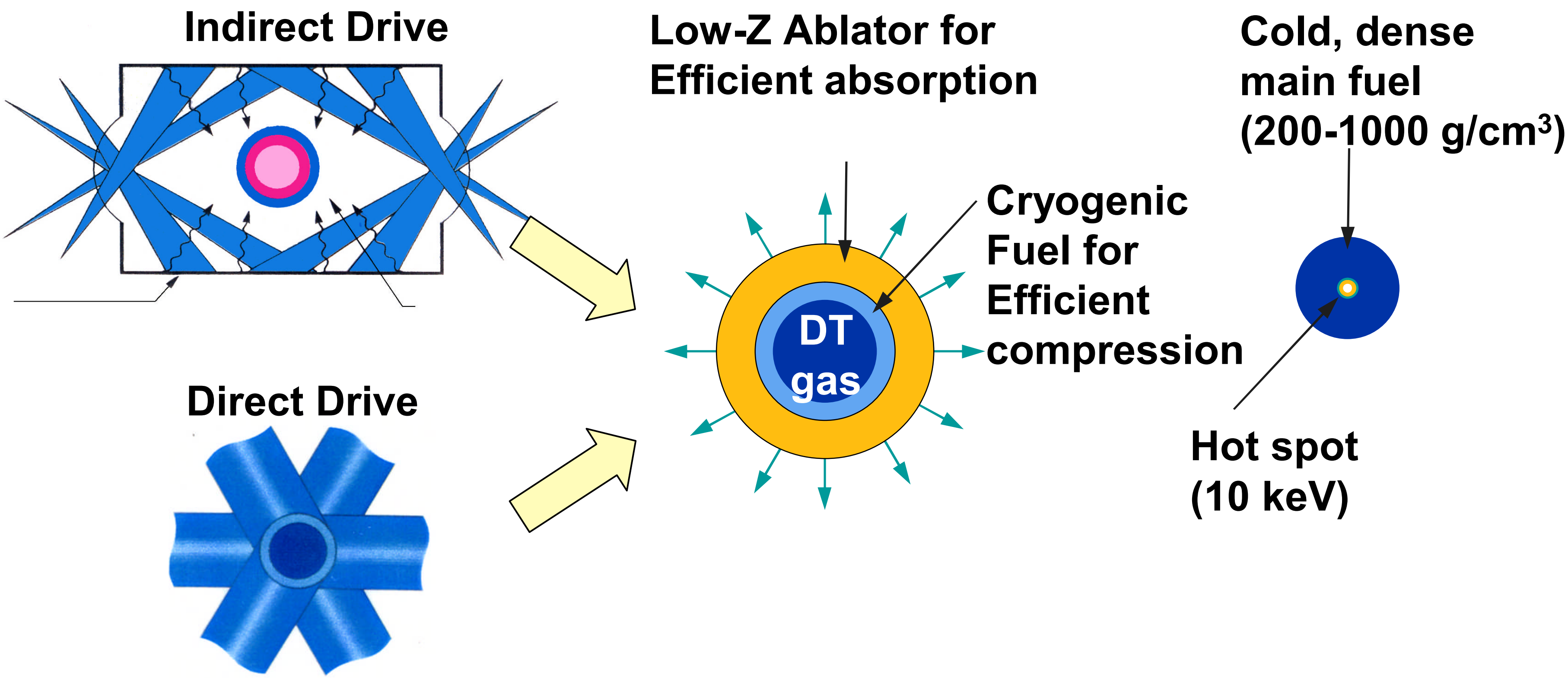

Inertial Confinement Fusion uses direct or indirect drive to couple driver energy to the fuel capsule

Spherical ablation with pulse shaping results in a rocket-like implosion of near Fermi-degenerate fuel

Spherical collapse of the shell produces a central hot spot surrounded by cold, dense main fuel

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

NIF can be used for both indirect and direct-drive ICF and High Energy Density (HED) Physics

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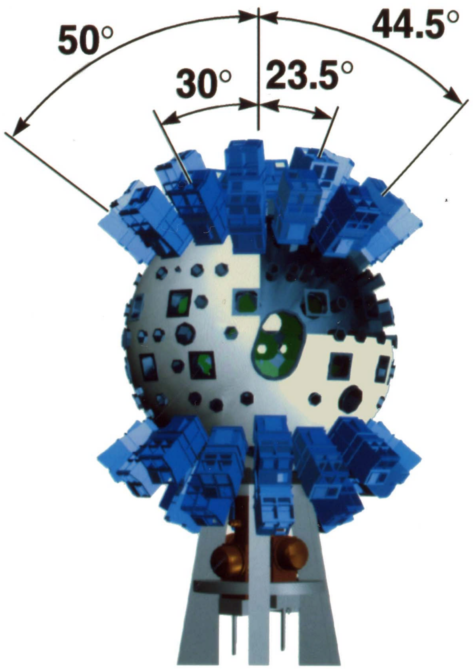
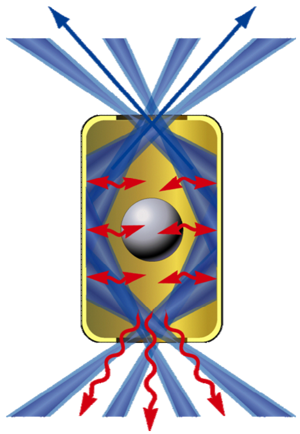
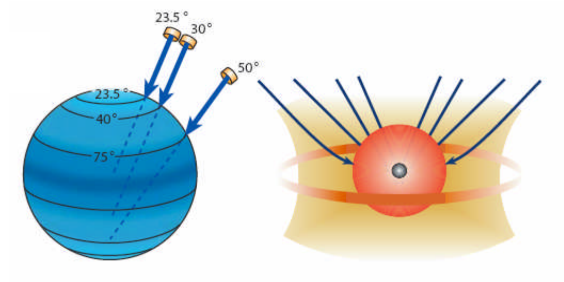


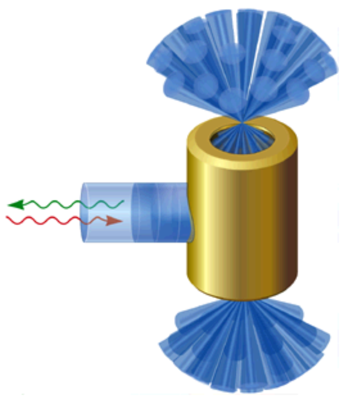
Indirect drive ICF



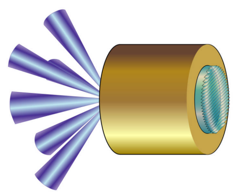
Direct drive ICF



Indirect drive HEDS

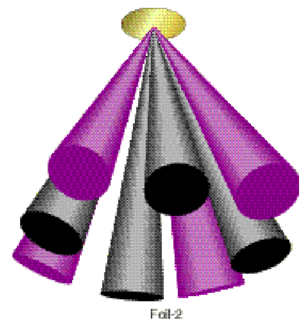


E.g. EOS



E.g. Hydrodynamics

Direct drive HEDS



E.g. Material Strength

NIF Indirect Drive target schematic

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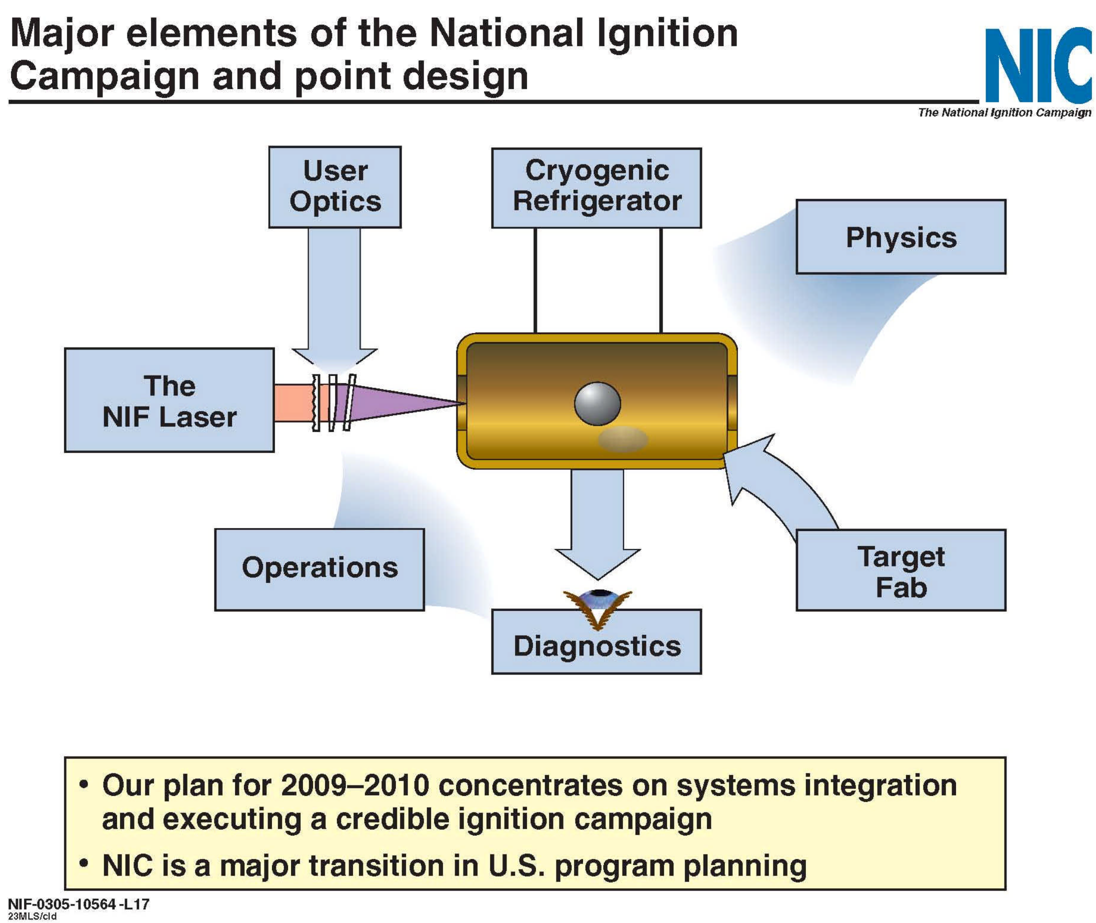

Cryogeni
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rings

cocktail)

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Laser Er
(LEH) wi

The success of NIF Early Light (NEL) experimental campaigns was due to efforts of multiple integrated experimental teams encompassing multiple laboratories

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	Shock Propagation	Laser-Plasma Interaction	Vacuum, Gas-Filled and Hot Hohlraums	Hydrodynamics
Experiments	P. Celliers, R. Collins, D. Bradley, J. Eggert, D. Hicks, M. Eckart, *P. Springer*	S. Glenzer, D. Froula, G. Gregori, R. Kirkwood, J. Knight, A. Mackinnon, C. Niemann, B. Young, W. Seka, *B. Hammel*	O. Landen, J. Fernandez,, M. Schneider, E. Dewald, H. Baldis, K. Campbell, G. Grim, R. Heeter, B. Hegelich, J. Kline, J. McDonald, D. Montgomery, G. Rochau, R. Olson, J. Schein, R. Turner, J. Workman, *B. Hammel*	H. Robey, N. Lanier, G. Glendinning, B. Blue, J. Foster, F. Hansen, T. Perry, M. Schneider, *W. Hsing*
Simulations	D. Braun, S. Moon, D. Munro	R. Berger, B. Cohen, L. Divol, O. Jones, W. Kruer, B. Langdon, S. Langer, N. Meezan, H. Rose, B. Still, E. Williams	L. Suter, D. Hinkel, D. Braun, E. Dodd, M. Edwards, S. Goldman, M.-C. Monteil, H. Rose, M. Stevenson, B. Thomas	R. Coker, G. Magelssen, P. Rosen, P. Stry, D. Woods, S. Weber, B. Wilde

Diagnostics

B. MacGowan, S. Alvarez, G. Armstrong, R. Bahr, J-L Bourgade, D. Bower, J. Celeste, M. Chrisp, S. Compton, J. Cox, C. Constantin, R. Costa, J. Duncan, A. Ellis, J. Emig, J. Foster, C. Gautier, A. Greenwood, R Griffith, F. Holdner, G. Holtmeier, D. Hargrove, T. James, J. Holder, J. Kamperschroer, J. Kimbrough, M. Landon, D. Lee, M. May, S. Montelongo, J. Moody, E. Ng, A. Nikitin, D. Pellinen, K. Piston, M. Poole, V. Rekow, M. Rhodes, R. Shepherd, S. Shiromizu, D. Voloshin, A. Warrick, P. Watts. F. Weber, B. Young, P. Young

NIF Facility & Laser

E. Moses, P. Arnold, L. Atherton, G. Bardsley, R. Bonanno, T. Borger, M. Bowers, R. Bryant, S. Buckman, S. Burkhart, F. Cooper, S. Dixit, G. Erbert, D. Eder, B. Ehrlich, B. Felker, J. Fornes, G. Frieders, S. Gardner, C. Gates, M. Gonzalez, S. Grace, T. Hall, C. Haynam, G. Heestand, M. Henesian, M. Hermann, G. Hermes, S. Huber, K. Jancaitis, S. Johnson, D. Kalantar, B. Kauffman, T. Kelleher, T. Kohut, A. E. Koniges T. Labiak, D. Latray, A. Lee, D. Lund, B. MacGowan, S. Mahavandi, K. R. Manes, C. Marshall, J. McBride, T. McCarville, L. McGrew, J. Menapace, E. Mertens, D. Munro, J. Murray, J. Neumann, M. Newton, P. Opsahl, E. Padilla, T. Parham, G. Parrish, C. Petty, M. Polk, C. Powell, I. Reinbachs, R. Rinnert, B. Riordan, G. Ross, V. Robert, M. Tobin, S. Sailors, R. Saunders, M. Schmitt,, M. Shaw, M. Singh, M. Spaeth, A. Stephens, G.Tietbohl, J. Tuck, B. Van Wonterghem, R. Vidal, P. Wegner, P. Whitman, K. Williams, K. Winward, K. Work, *G. Miller*

E. Moses, WP3.2

Target Fabrication

R. Wallace, A. Nobile, M. Bono, B. Day, J. Elliott, D. Hatch, H. Louis, R. Manzenares, D. O’Brien, P. Papin, T. Pierce, G. Rivera, J. Ruppe, D. Sandoval, D. Schmidt, W. Steckle, L. Valdez,, K. Zapata

First quad NIF experiments successfully exercised all existing facility capabilities and delivered new results

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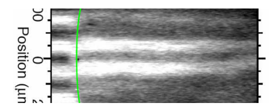
Diagnostics

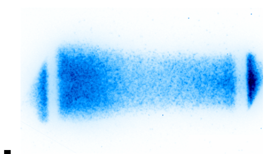
•Every type of optical and x-ray facility diagnostic successfully commissioned

Shock Propagation



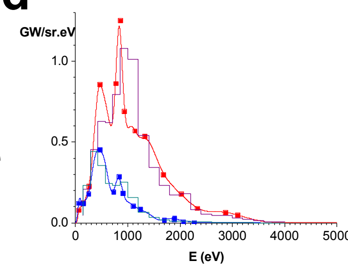
•Planar, steady long pulse direct-drive capability demonstrated

Laser-Plasma Interaction



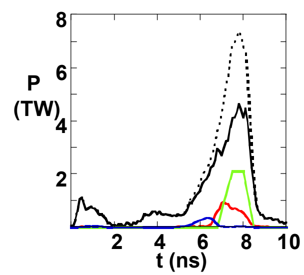
•Good laser propagation in long-scale length low Z plasma demonstrated, confirming understanding of filamentation threshold

Vacuum and Hot Hohlraums



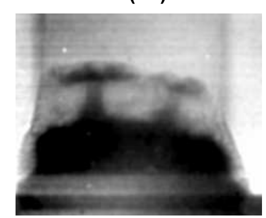
•Vacuum hohlraum performance agree with simulations and probe limits due to plasma filling

Gas-Filled Hohlraums



•High contrast shaped-pulse gas-filled hohlraum energetics help understanding of laser-plasma interactions

Hydrodynamics



•Study of hydrodynamic jet evolution extended to 3D and dual features

Diagnostics

NIF commissioned a broad suite of optical and x-ray diagnostics for early experiments

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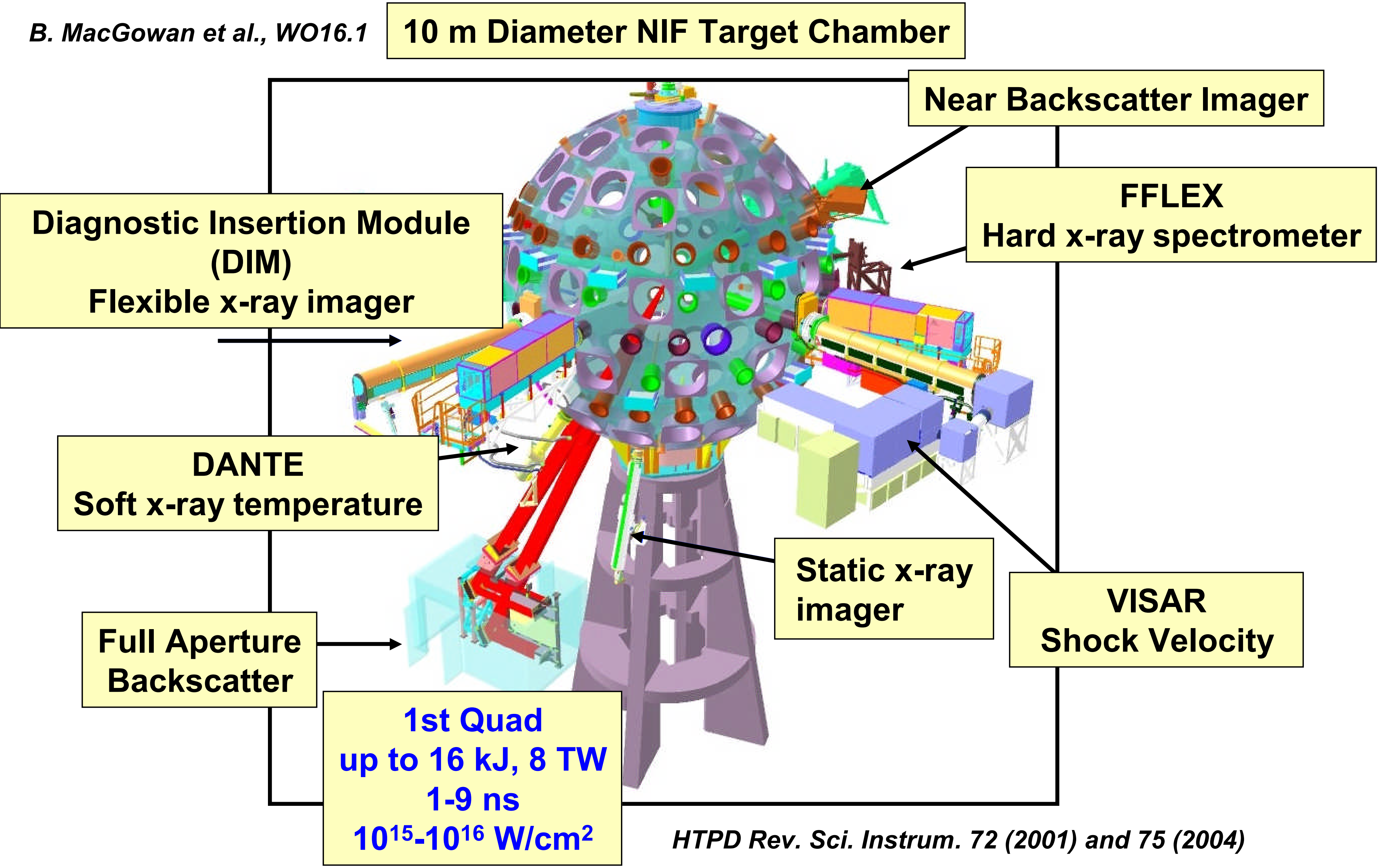
B. MacGowan et al., WO16.1



HTPD Rev. Sci. Instrum. 72 (2001) and 75 (2004)

Diagnostics

Two Diagnostic Insertion Manipulators (DIM) installed for use on all NIF 1st Quad campaigns

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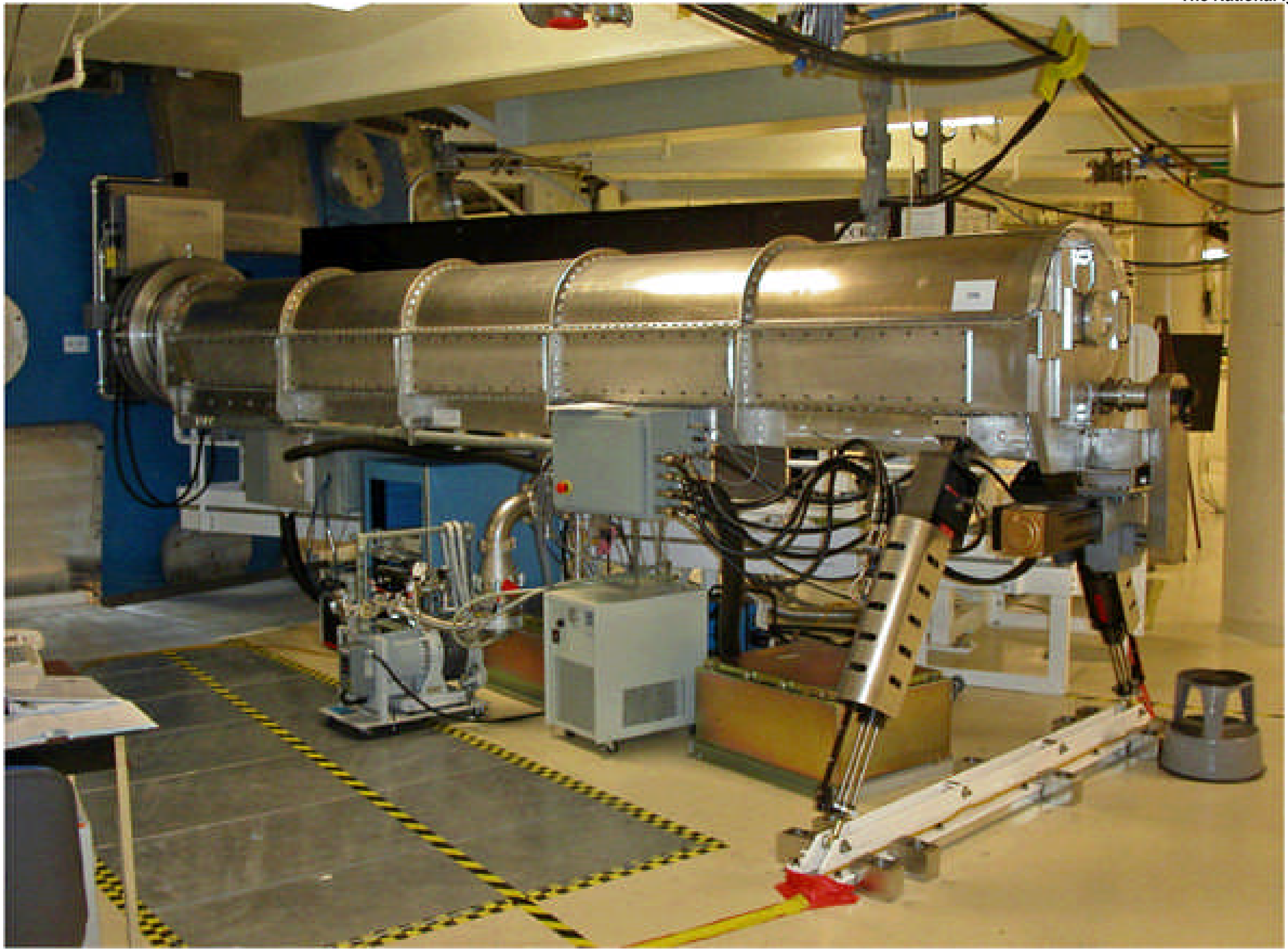
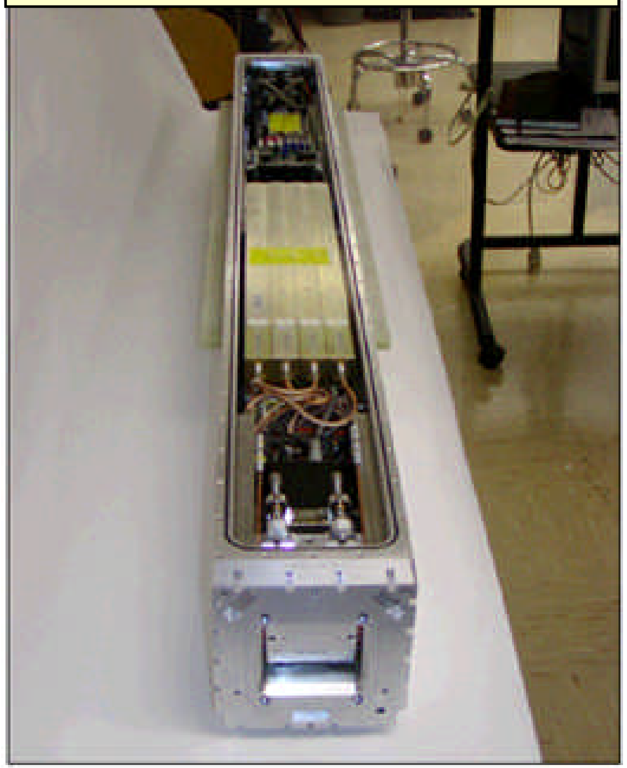


Using opposing port telescope, we aligned DIM-based instruments to 50 μm, 2x better than required

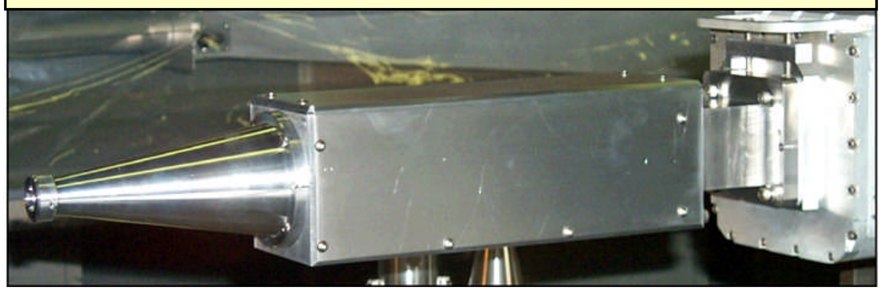
DIM-insertable hard or soft x-ray streak and framing cameras were essential to first campaigns

First DIM-based X-ray Framing Camera in Air Box

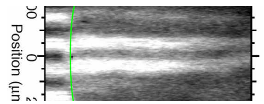
LANL Gated X-ray Camera in Air Box



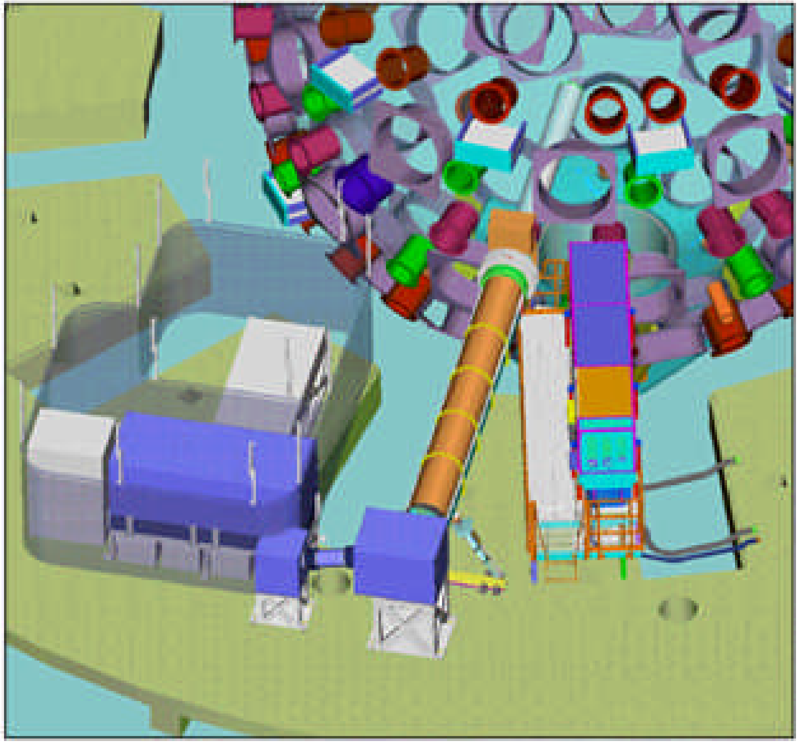
Soft X-ray Imaging Snout

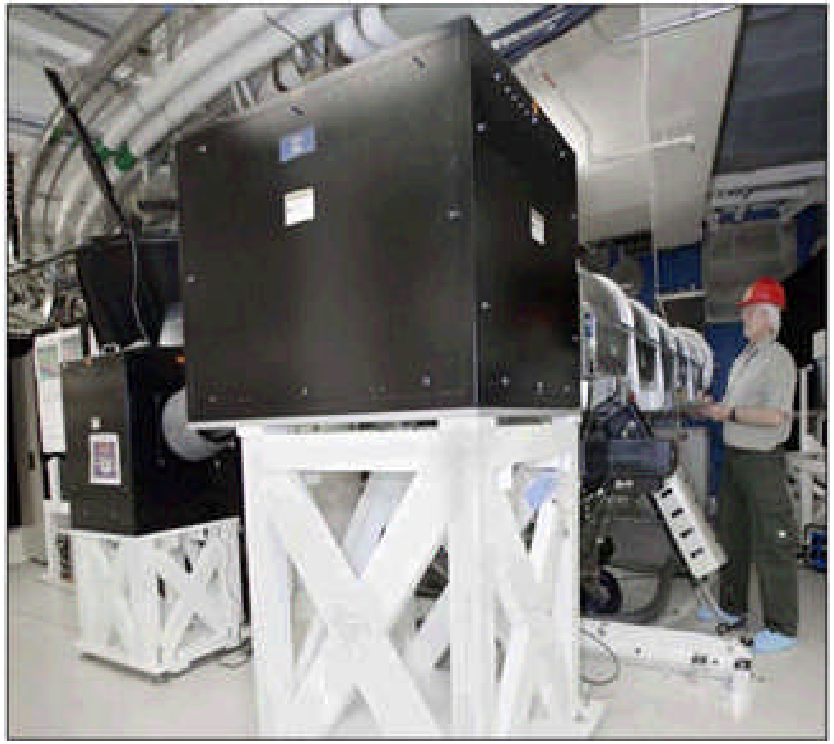


Shock Propagation

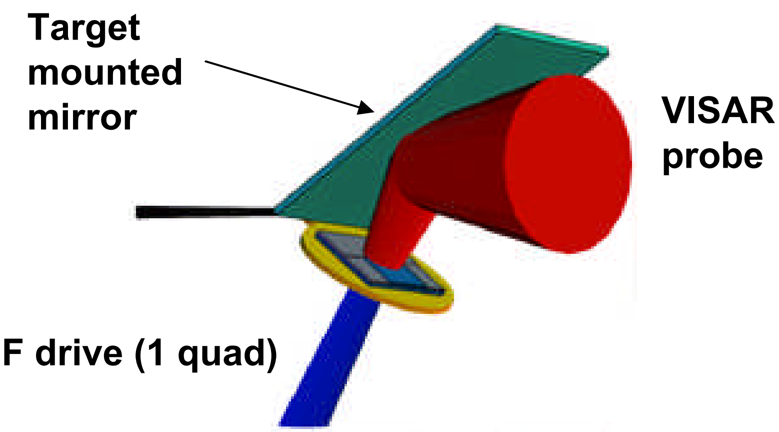


660 nm VISAR Interferometer commissioned for performing planar shock timing



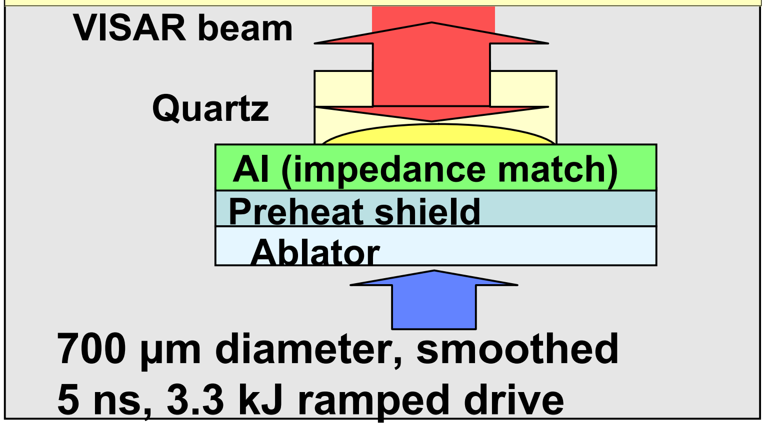


Normal incidence drive

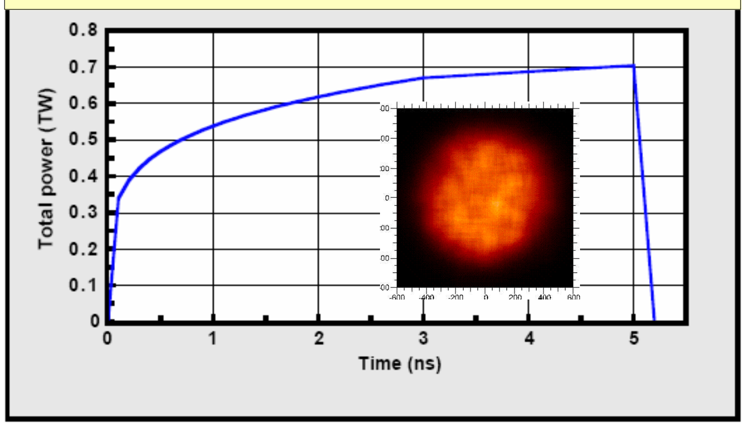


NIF planar direct-drive experiment demonstrated expected shock strength, steadiness and planarity

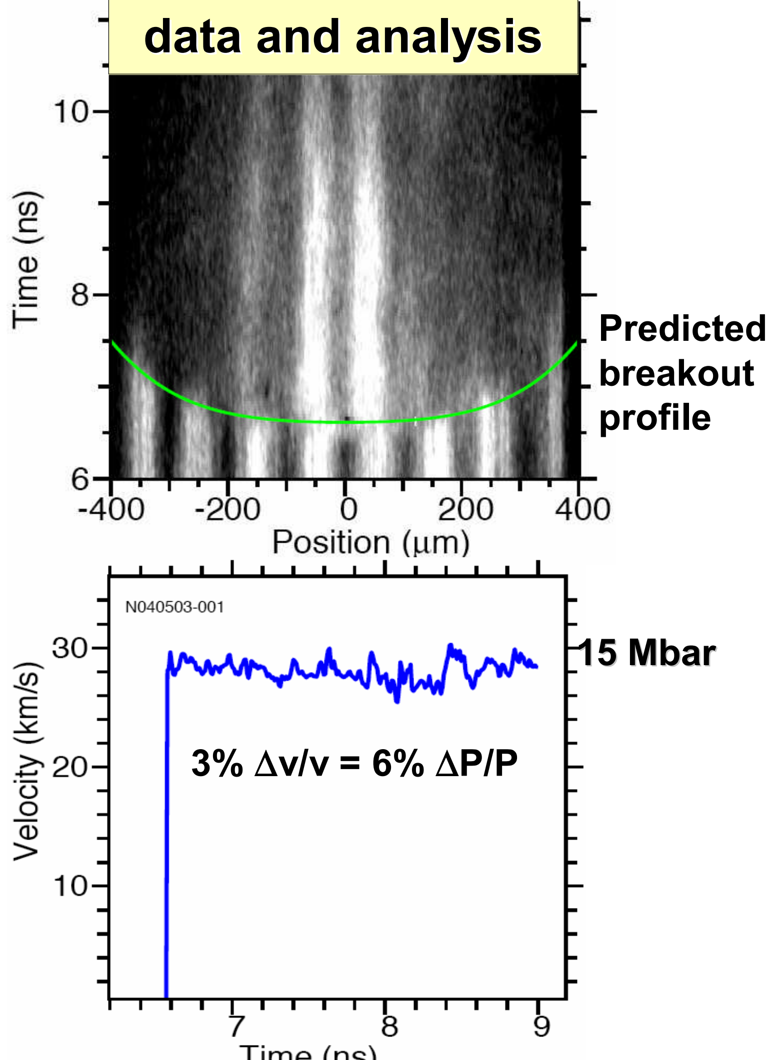
Setup for long steady drive demonstration



Drive pulse profiles

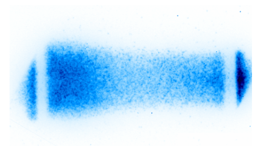


VISAR streaked data and analysis



- Pressure within 10%, meeting requirement
- Shock steadiness to < 3%, exceeding 5% requirement
- Shock planar to 5% over 500 µm, meeting requirement

Laser-Plasma Interaction



Diagnostics

An international team successfully activated laser coupling and hohlraum capability using NIF 1st quad

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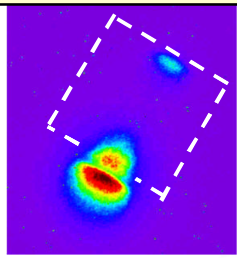
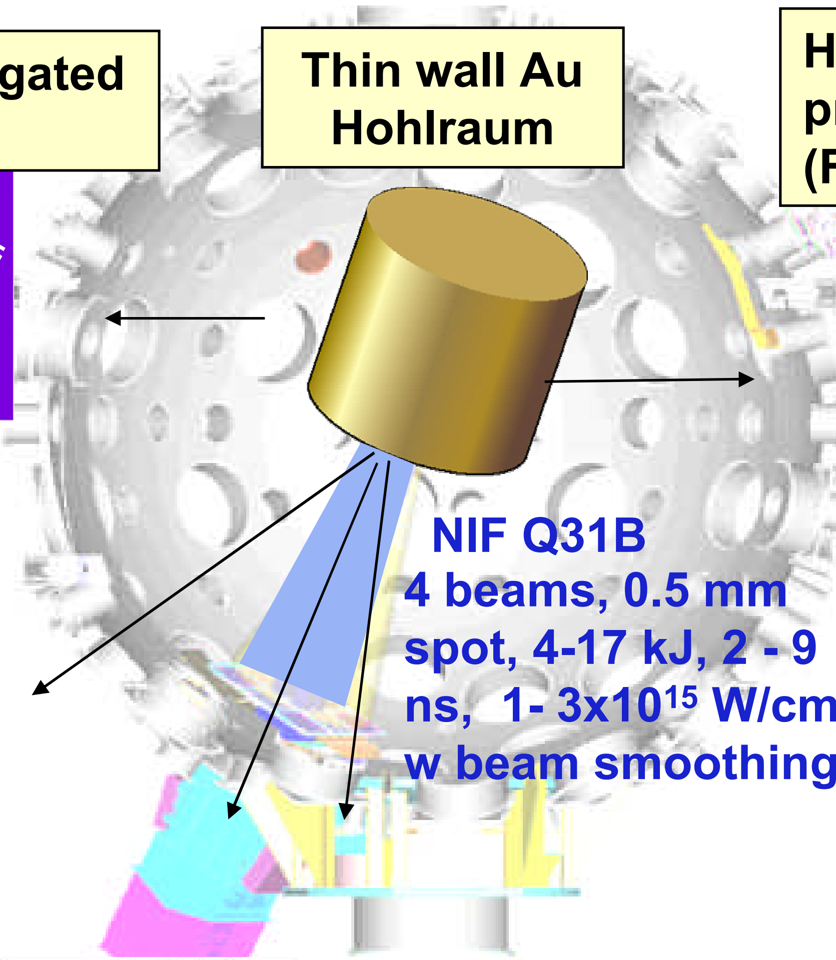
Plasma filling (9 keV gated x-ray imaging), 84.4º



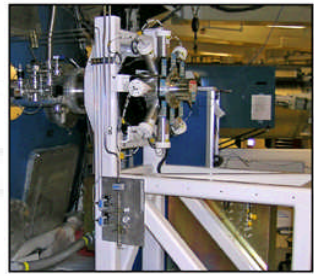
Thin wall Au Hohlraum



NIF Q31B
4 beams, 0.5 mm spot, 4-17 kJ, 2 - 9 ns, 1- 3x10^{15} W/cm^2 w beam smoothing

Hot electron production (FFLEX) 113º

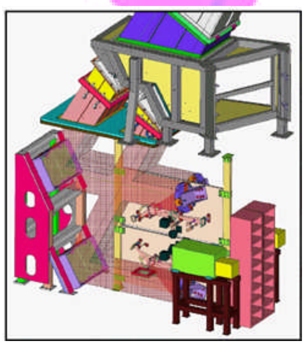
AWE

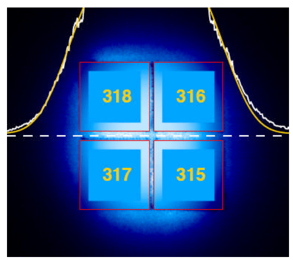


8 channel, 20-120 keV, Absolute, time integrated

Hohlraum Temperature (Dante) 21.6º

18 channel, 0.1-10 keV, Absolute, time resolved





Laser Backscatter (SBS and SRS) in lenses (FABS) and outside the lenses (NBI)

Laser propagation and coupling studied as function of smoothing in long-scale low Z gas tubes

Laser-Plasma Interaction

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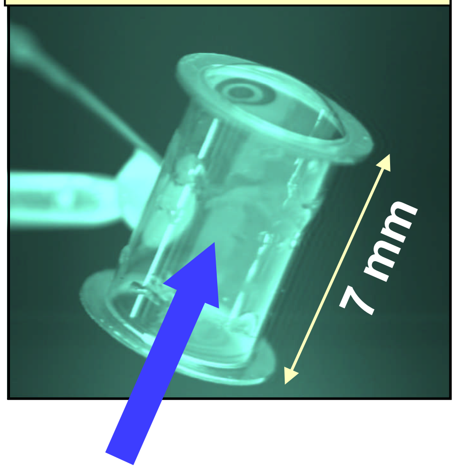
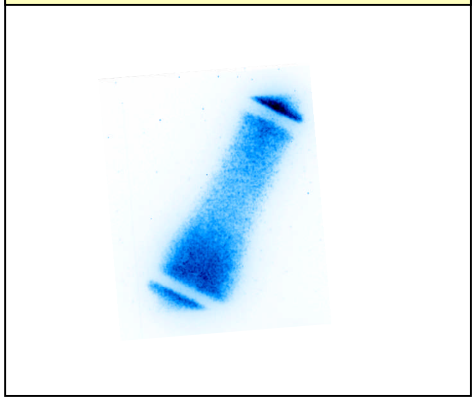
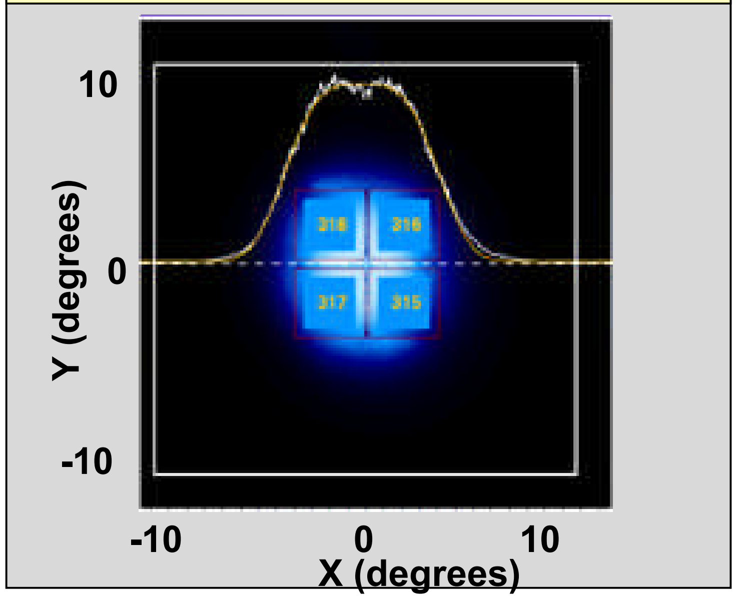
1 atm. CO_2 filled gas tube (7% n_c)



Gated x-ray image of laser-plasma



Backscatter distribution reconstruction



2.5x10^{15} W/cm^2
16 kJ in 3.5 ns
500 µm Phase-Plate (CPP)
with and without 90 GHz SSD + PS

Dixit et al., TuPo7

Birefringent wedged crystal provided Polarization Smoothing (PS) option by reducing power in intense speckles

S. Glenzer et al., Nuc. Fusion 44 (2004) S185

Gas-tubes demonstrated control and suppression of filamentation in NIF ignition scale low Z plasmas

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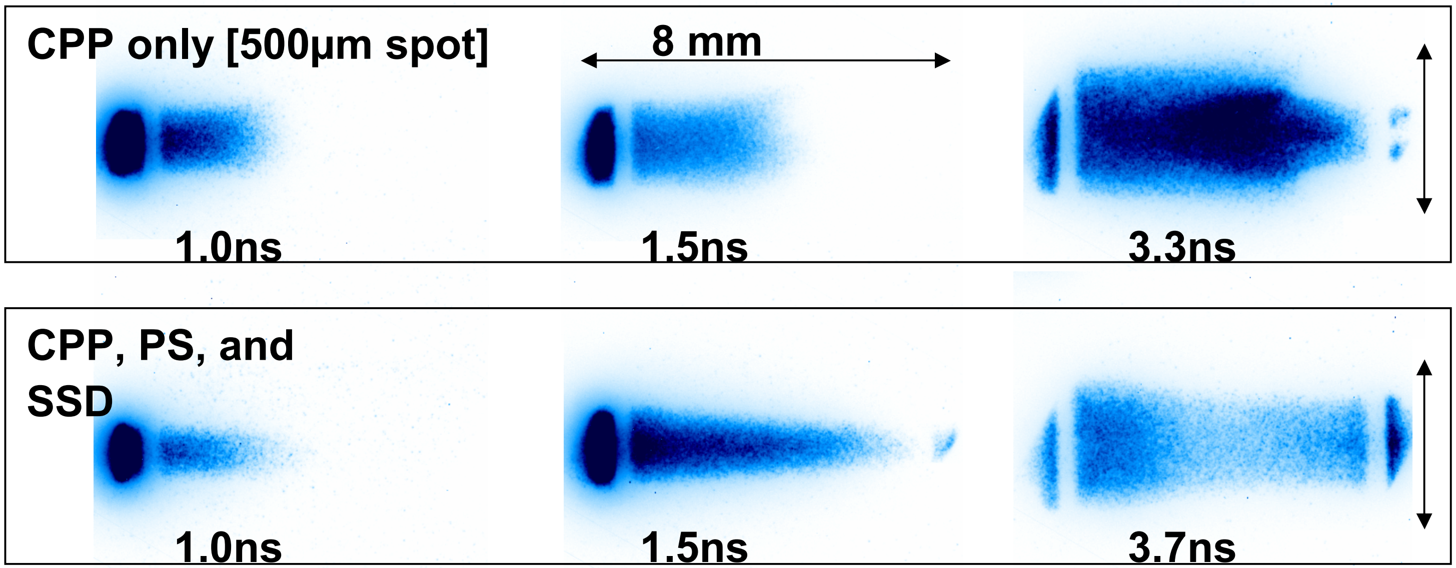
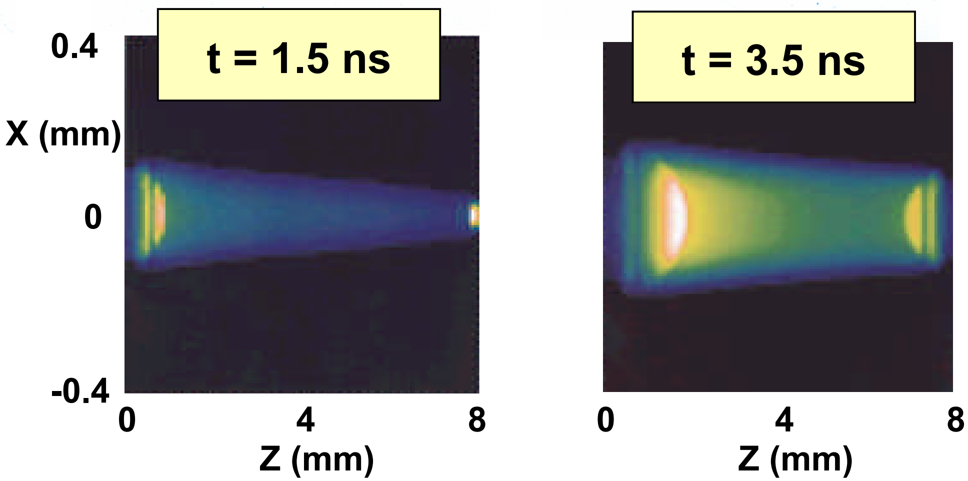
3.5 keV X-ray images of beam propagation

Data



LASNEX ray tracing simulations including backscatter losses agree with laser propagation when PS and SSD added



D. Froula, S. Glenzer et al., WPo13.6

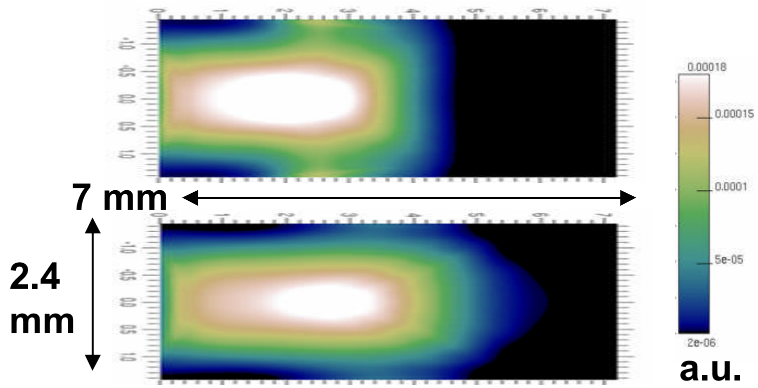
Preliminary fine-scale simulations (pF3D) confirm faster burnthrough and reduced filamentation with PS, SSD

pF3D X-ray images of beam propagation

CPP

t = 2.5 ns

CPP + SSD + PS

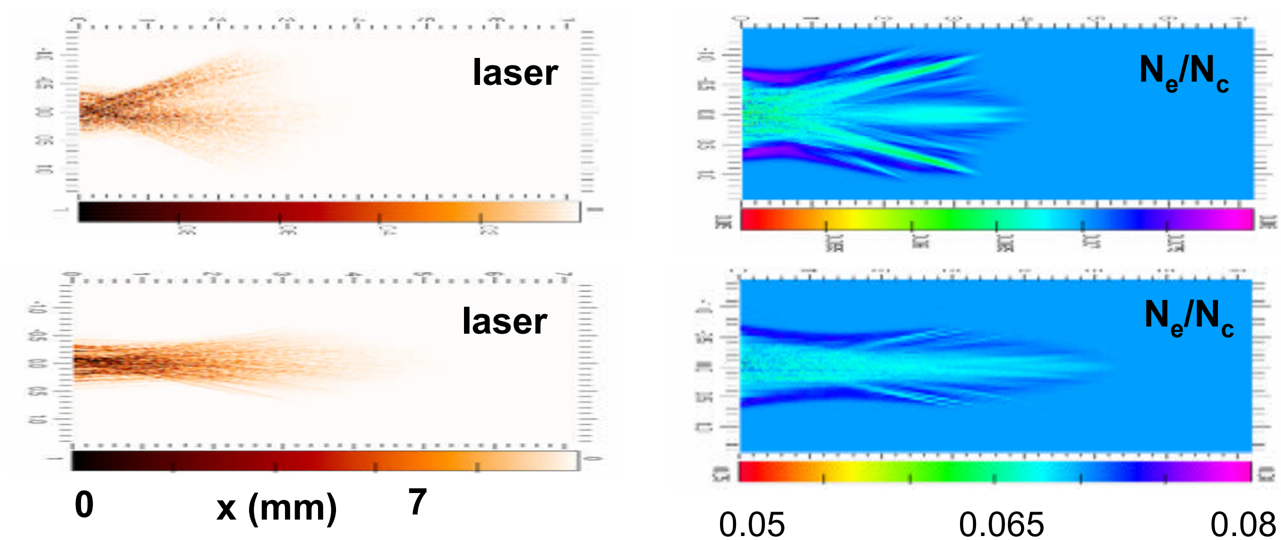


pF3D laser propagation and density profiles

CPP

t = 0.5 ns

CPP + SSD + PS



Future simulations will include window and self-consistently calculate backscatter

Improved beam smoothing leads to increase in filamentation threshold and reduction in beam spray

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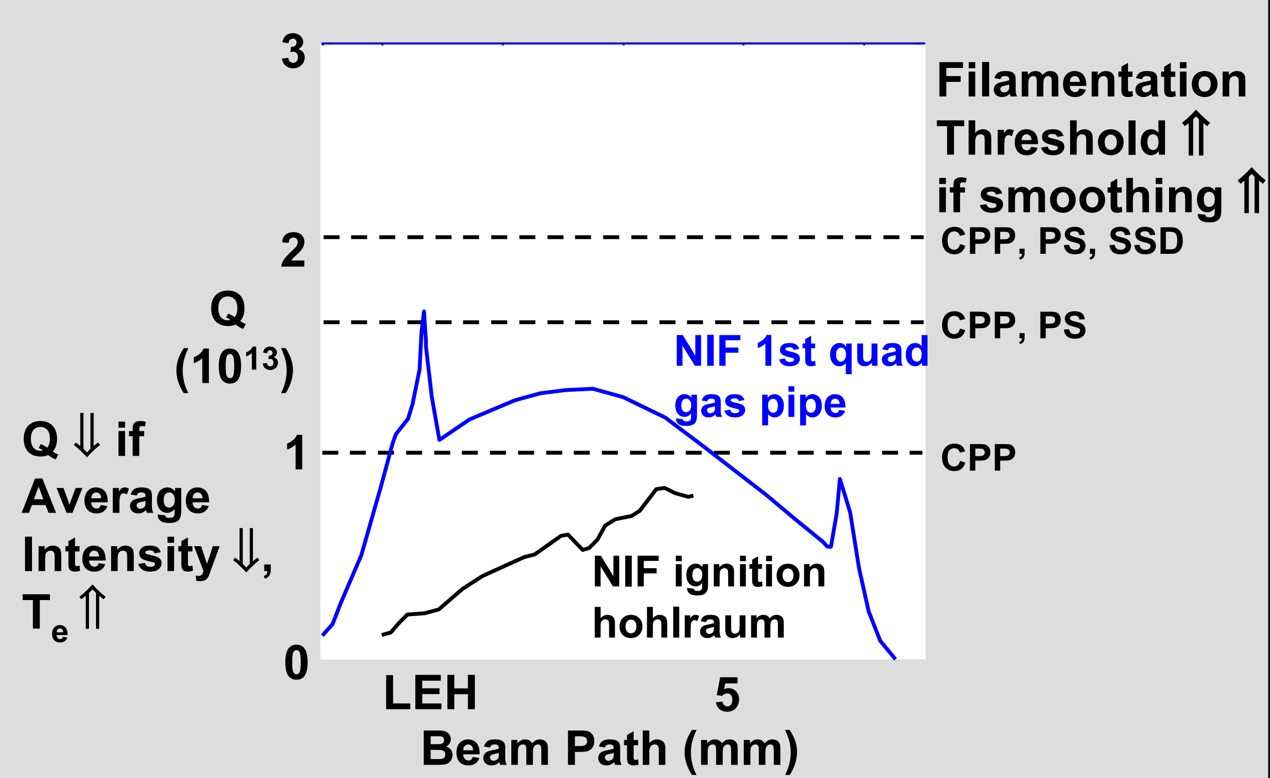
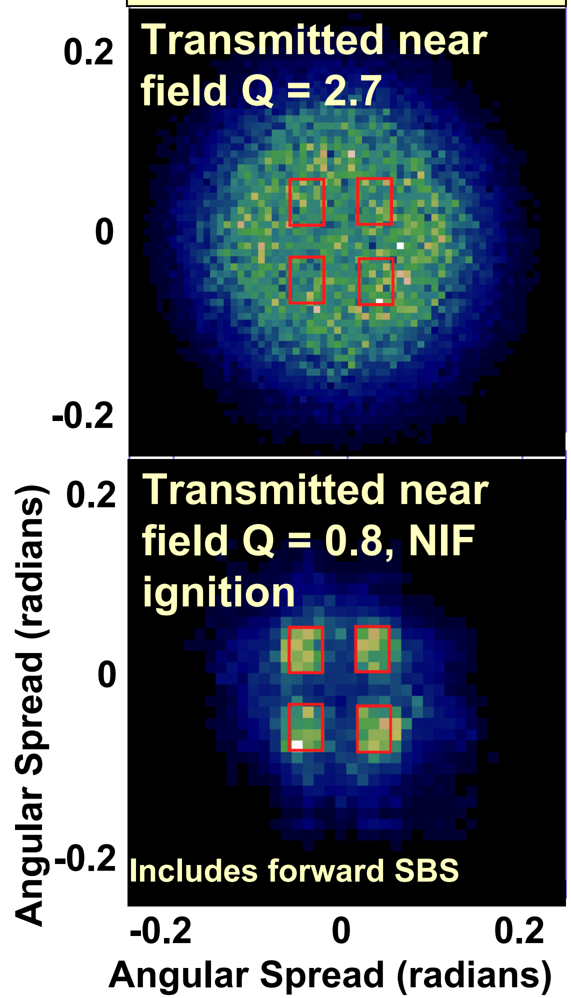
_Filamentation (FoM) at peak T_e

$Q = I\,[\mathrm{Wcm^{-2}}]\ \lambda^2[\mu\mathrm{m}^2]\ n_e/n_c\ 3/T_e[\mathrm{keV}]\ (f\#/8)^2$

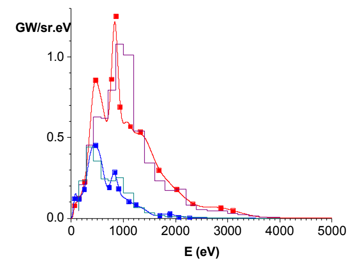


NIF ignition hohlraums will stay well below filamentation threshold by using all beam smoothing options *and* keeping intensities below 2×10^{15} W/cm²

Calculated near fields vs Q FoM



Vacuum and Hot Hohlraums



18 channel absolutely calibrated "Dante" power diagnostic measured 50 eV - 10 keV spectrum

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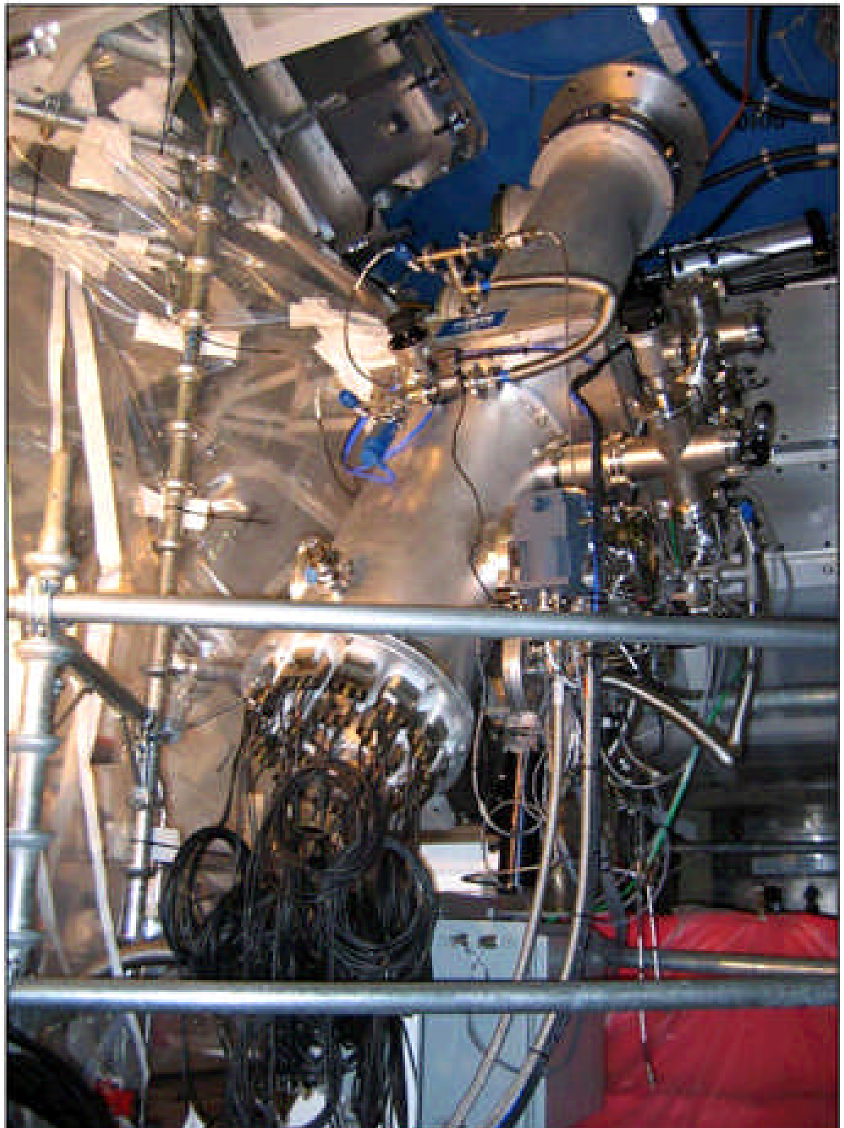
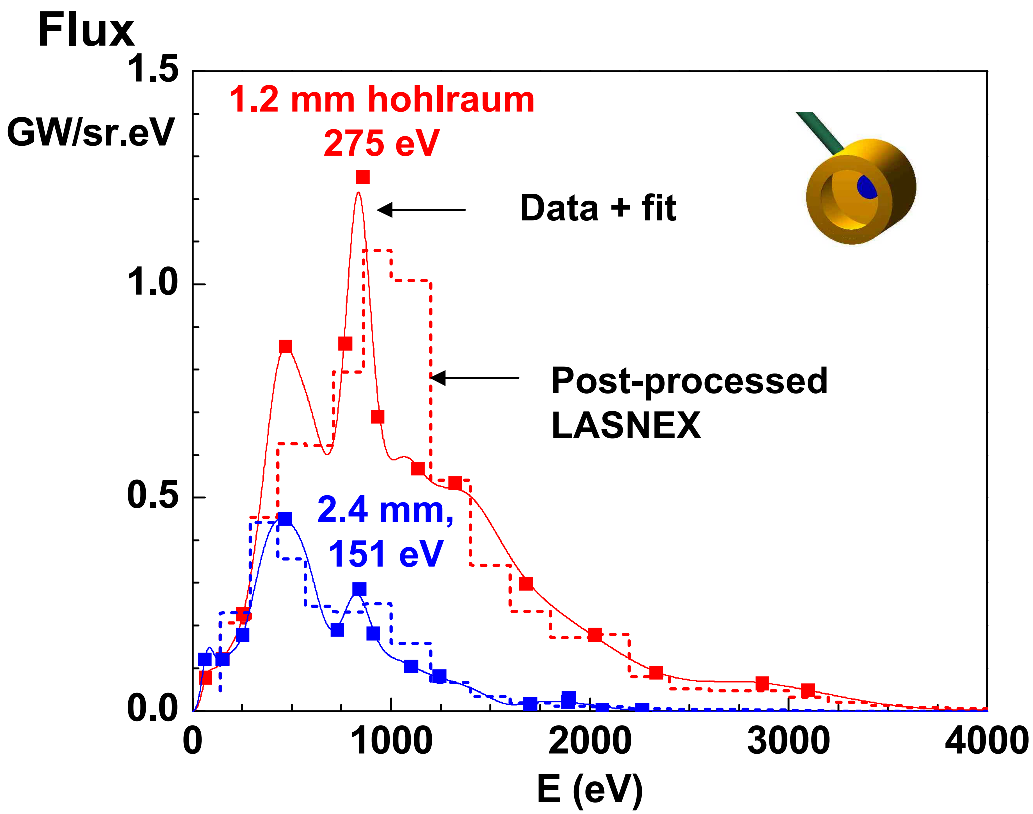


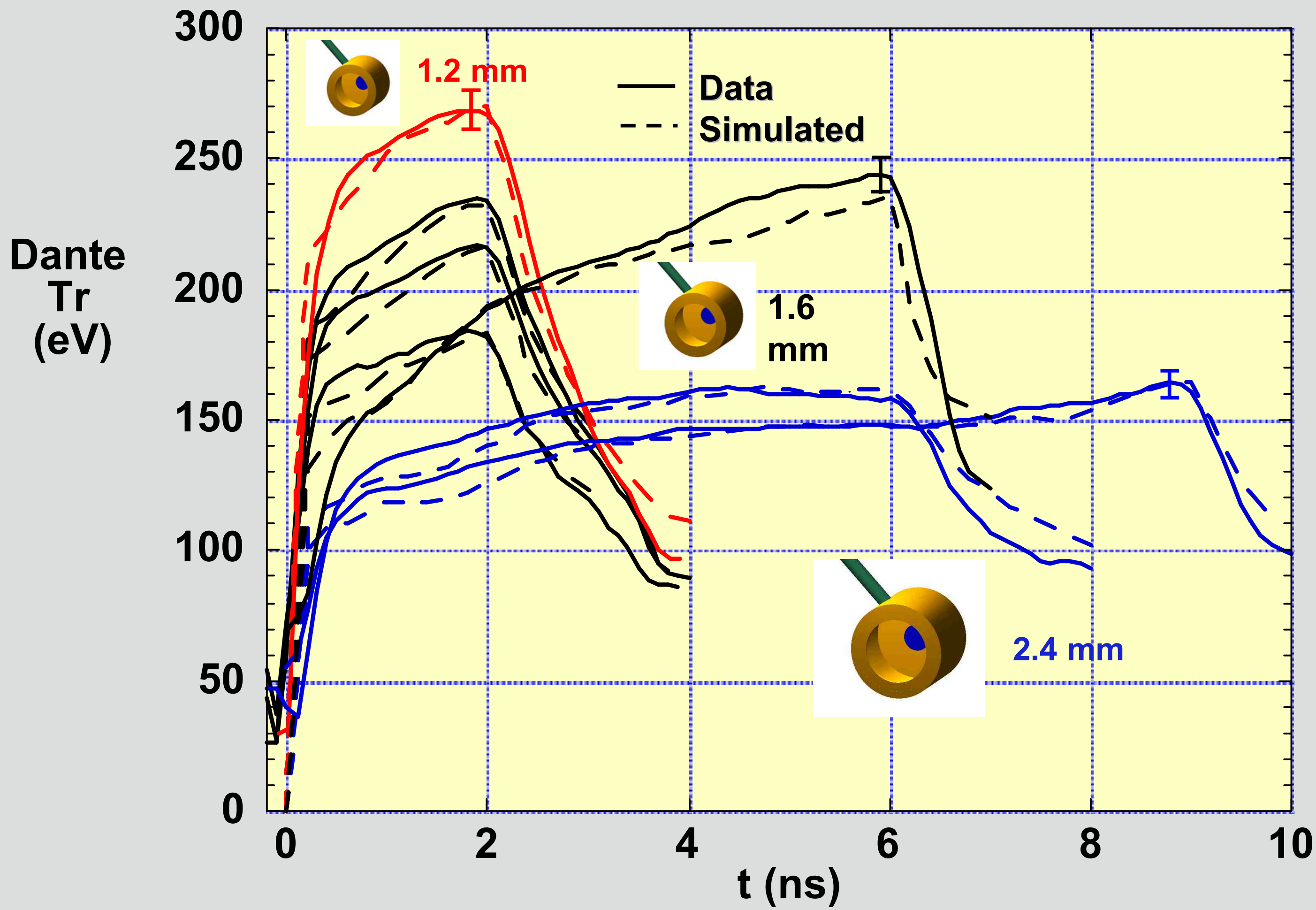
Dante diode array – time resolved radiation drive

Measured and simulated Dante spectra at the end of the drive



Total flux divided by source size yielded a radiation temperature to 2-3% accuracy

A variety of vacuum hohlraums driven with 2 - 9 ns pulses demonstrated expected radiation temperature



Peak T_{RAD} matches simulations within 2-3% Dante uncertainty
Negligible backscatter and hot electron fraction (< 1%) for all vacuum hohlraums < 300 eV

Small vacuum hohlraums driven with smaller spots reached expected > 330 eV radiation temperatures

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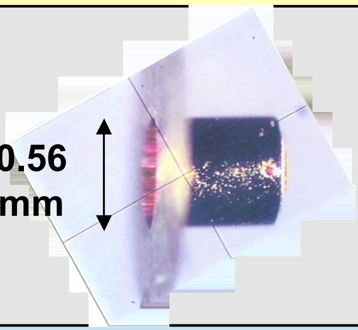
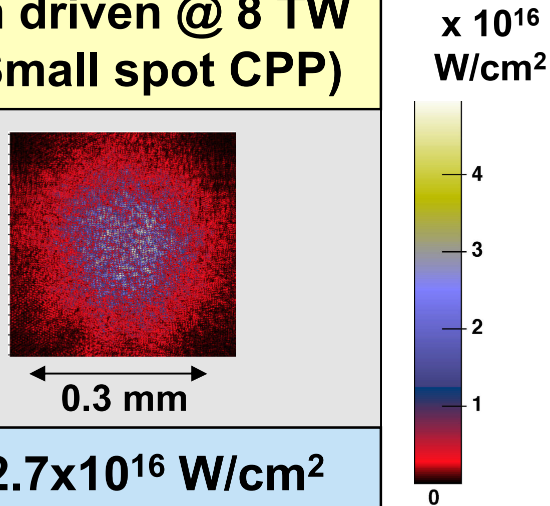
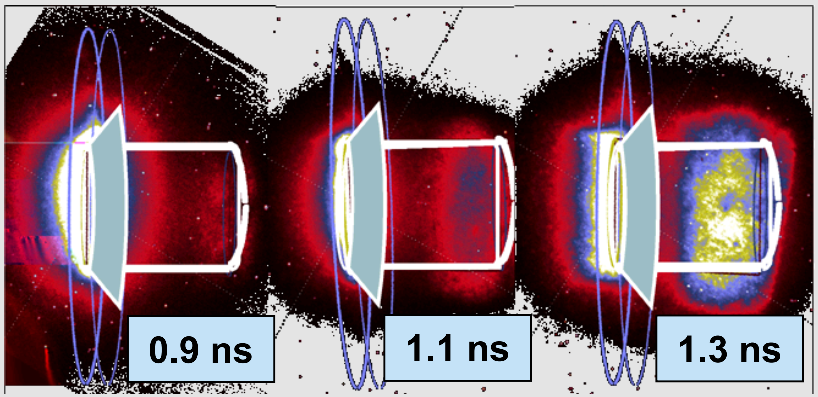
3.5 µm-thick hohlraum driven @ 8 TW
1.2 ns Flattop beam (Small spot CPP)





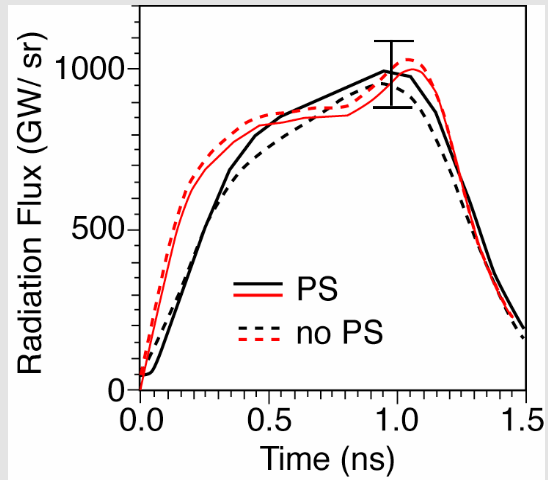
< 10% power above 2.7×10^{16} W/cm²

1 keV images of x-ray burnthrough



Measure of gradients in internal hohlraum energetics

Measured vs simulated flux



PS Exp:	T_{rad} = 340 eV	
Lasnex:*	T_{rad} = 337 eV	
No PS Exp:	T_{rad} = 340 eV	
Lasnex:*	T_{rad} = 343 eV	

*Accounting for 10% backscatter

D. Hinkel et al., M03.2

M. Schneider et al., WPo13.x

Signatures of plasma filling observed as predicted when hohlraum size decreased for fixed drive

Vacuum and Hot Hohlraums

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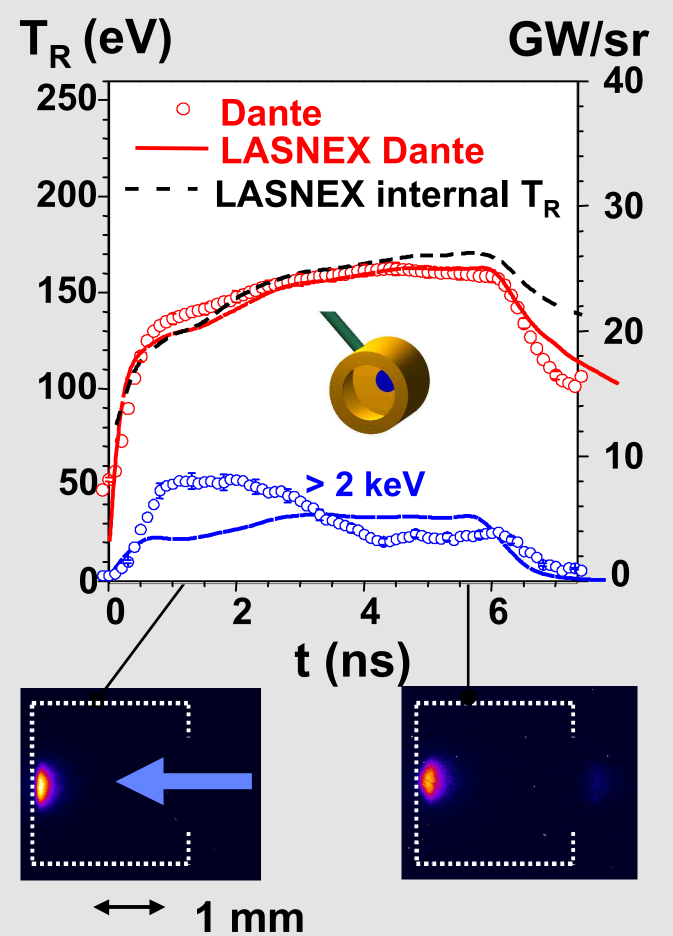
2.4 mm Hohlraum



Filling minimal; Dante Tr ≈ internal Tr at all t

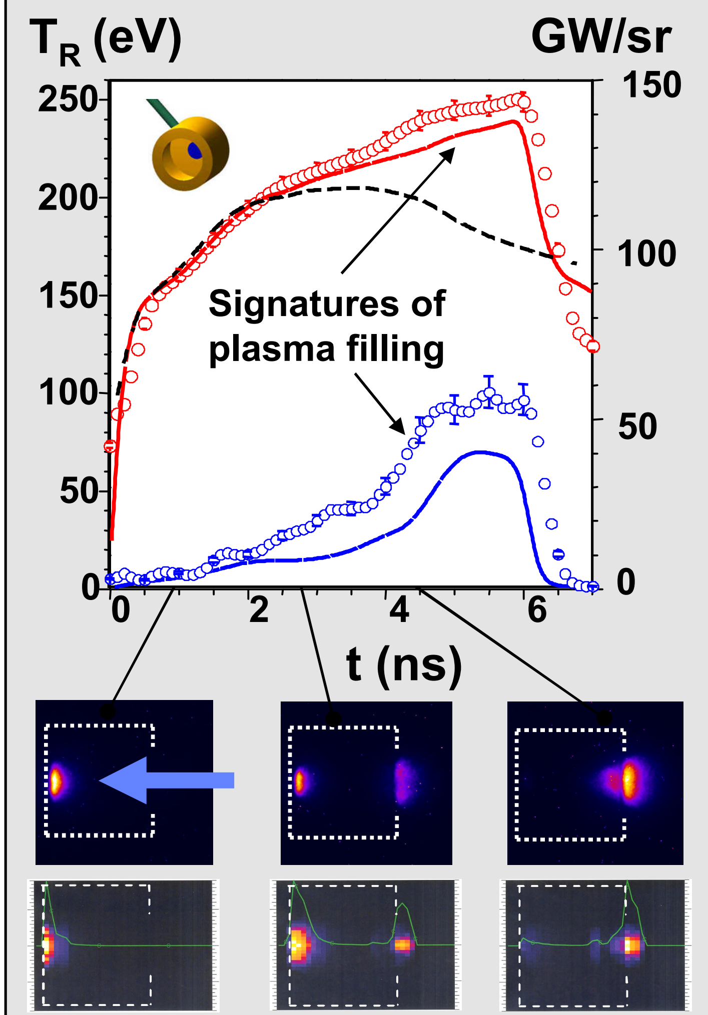
16 kJ, 6 ns Flattop drive

9 keV X-ray images

Data

Simulations

1.6 mm Hohlraum



Filling important; Hard x-rays ⇑, Dante Tr ⇑, internal Tr ⇓

First NIF quad hohlraum Tr limits used to predict full NIF vacuum hohlraum performance limits

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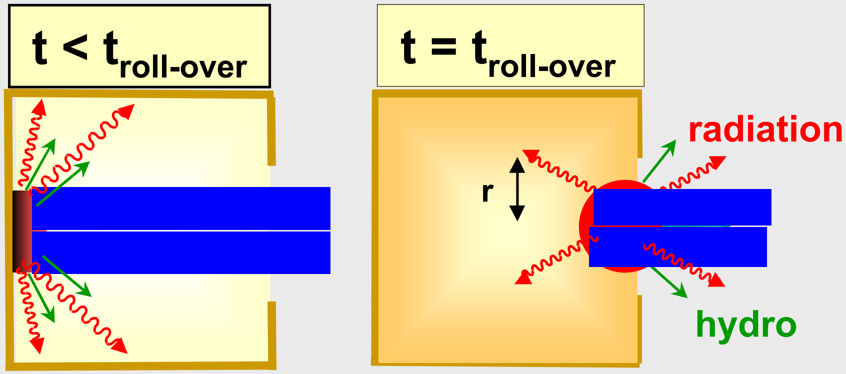
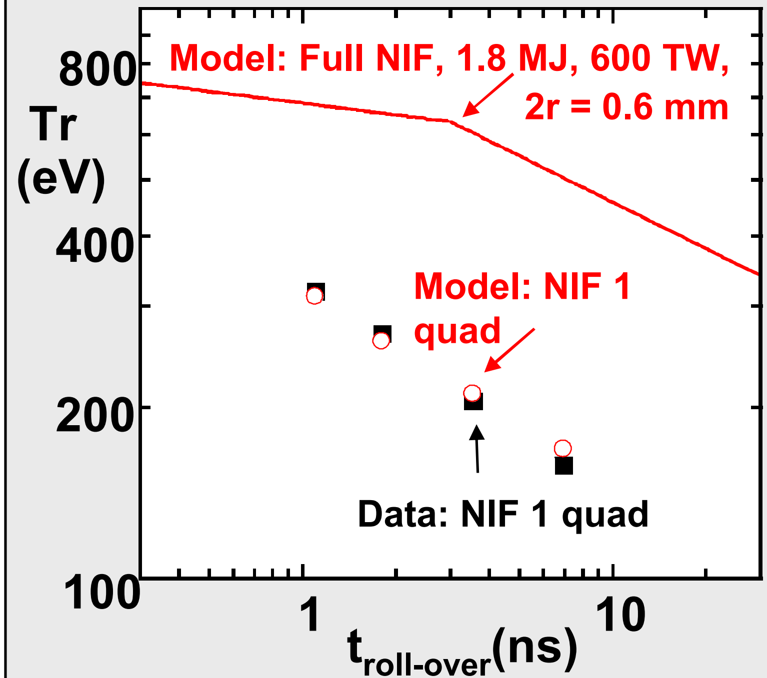
Analytic Plasma Fill Model



When I.B. absorption length comparable to LEH radius r , hydrodynamic and coronal radiative losses out of LEH ⇑ and internal Tr ⇓

Plasma parameters from (J. Lindl 1995):
X-ray ablated plasma pressure = Laser channel pressure
Heat conduction loss = I.B. heating
Hohlraum power balance

Tr vs t limits: analytic model and data

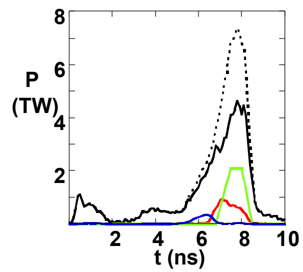


$$T_R = 1.0\, P_L^{0.2} / r^{0.2}\ t^{0.07} = 1.0\, E_L^{0.2} / r^{0.2}\ t^{0.27}$$

T_R (heV), P_L (TW), E_L (kJ), r (cm), t (ns)

E.L. Dewald, L.J. Suter, O.L. Landen et. al., submitted to Phys. Rev. Lett.

Gas-Filled Hohlraums



We also demonstrated a high-contrast, long-pulse, low Z gas-filled hohlraum drive of the type used for ignition

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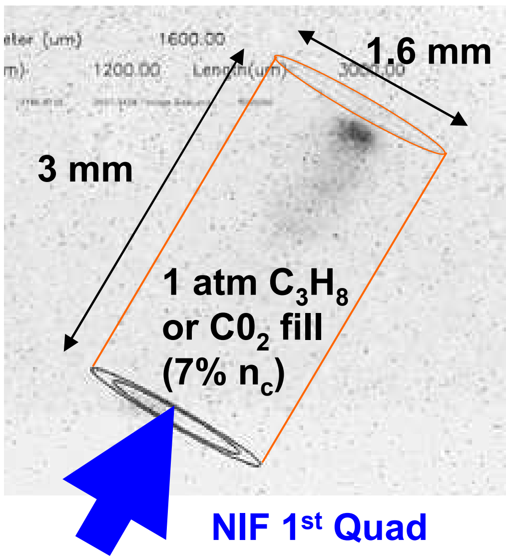
10 keV X-ray image of laser plasma @ peak of pulse

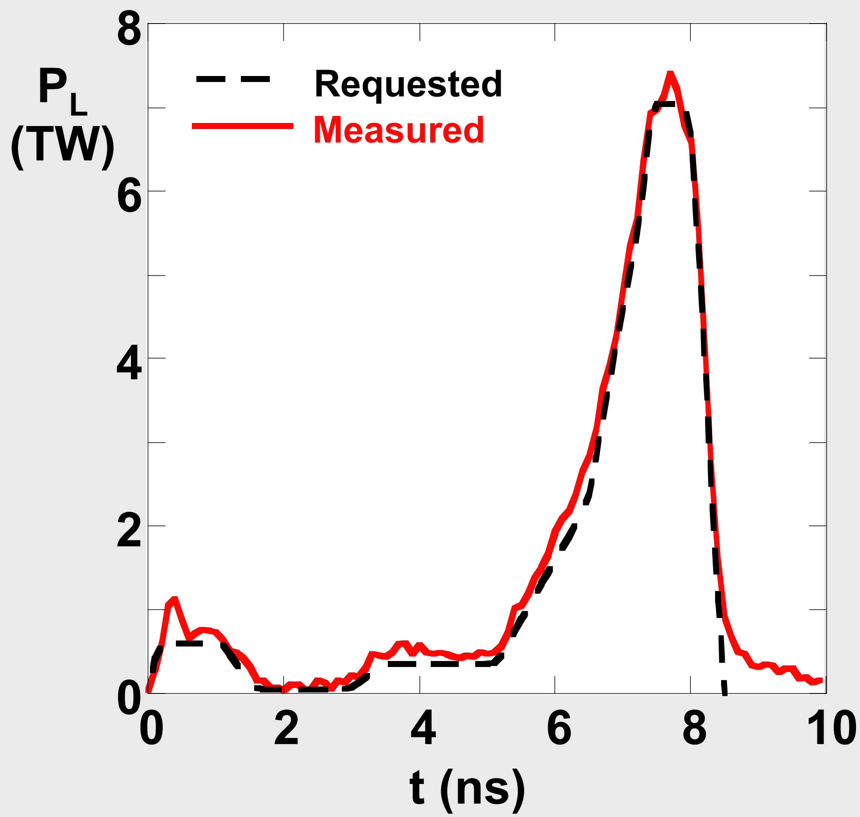


500 µm smoothed spot (CPP + PS)

J. Fernandez et al., TuO7.1

S. Goldman et al., MO2.6

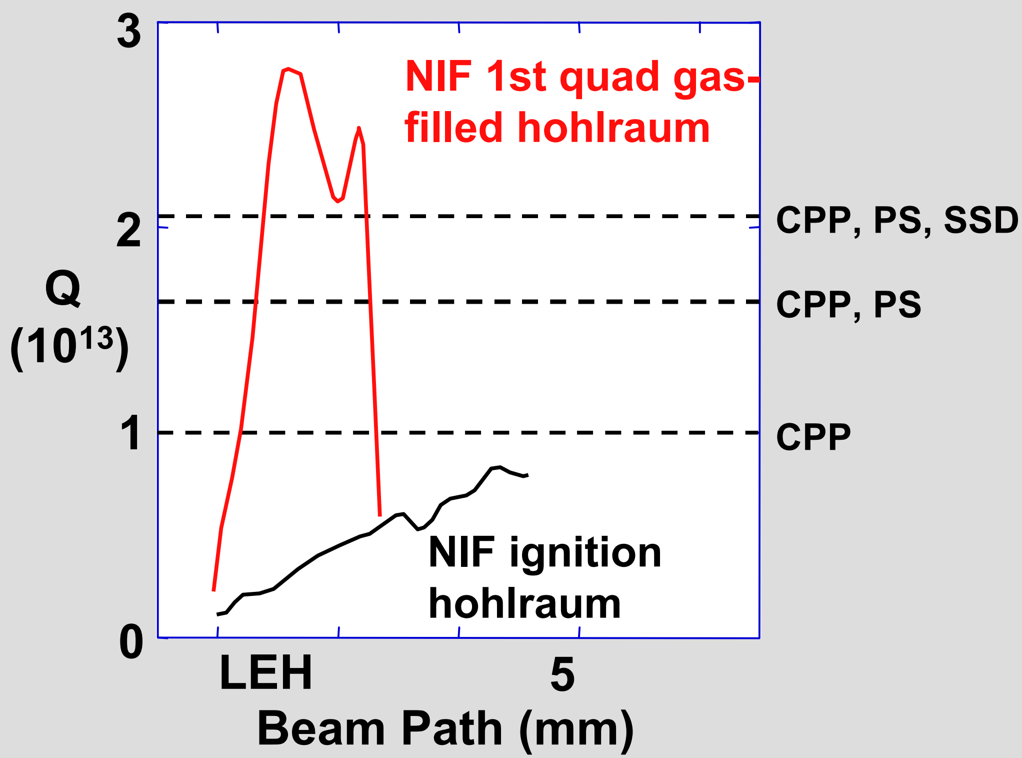
Comparison of requested and measured 120:1 contrast ratio pulse



C. Haynam et al., WO16.2

Peak intensity was 3×10^{15} W/cm^2, above ignition design beam intensities and above filamentation threshold

Filamentation Figure-of-Merit at Peak Intensity



NIF ignition hohlraum designs keep peak intensities < 2×10^{15} W/cm^2 and assume full smoothing applied (CPP, PS, SSD) to mitigate filamentation and beam spray

Measured and calculated gas-filled hohlraum energetics agree when including backscatter losses

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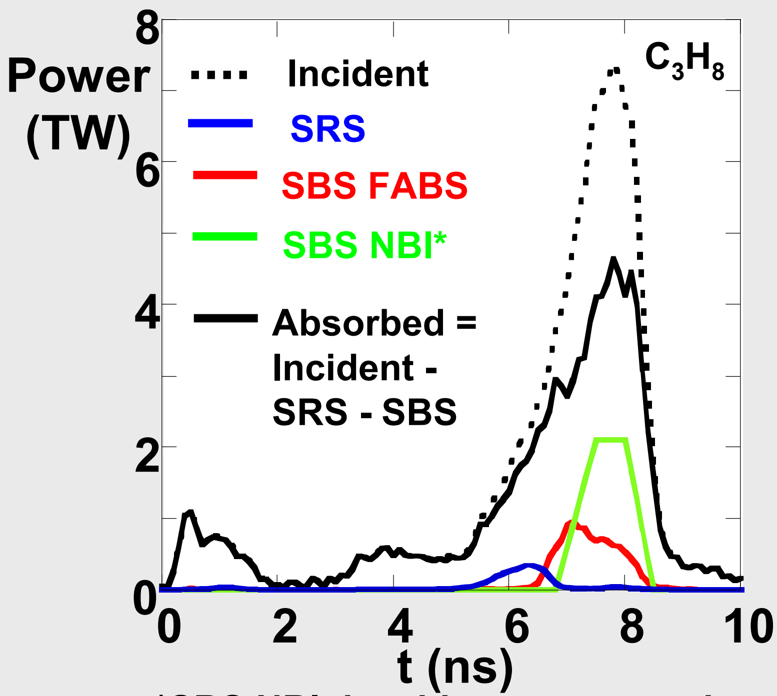
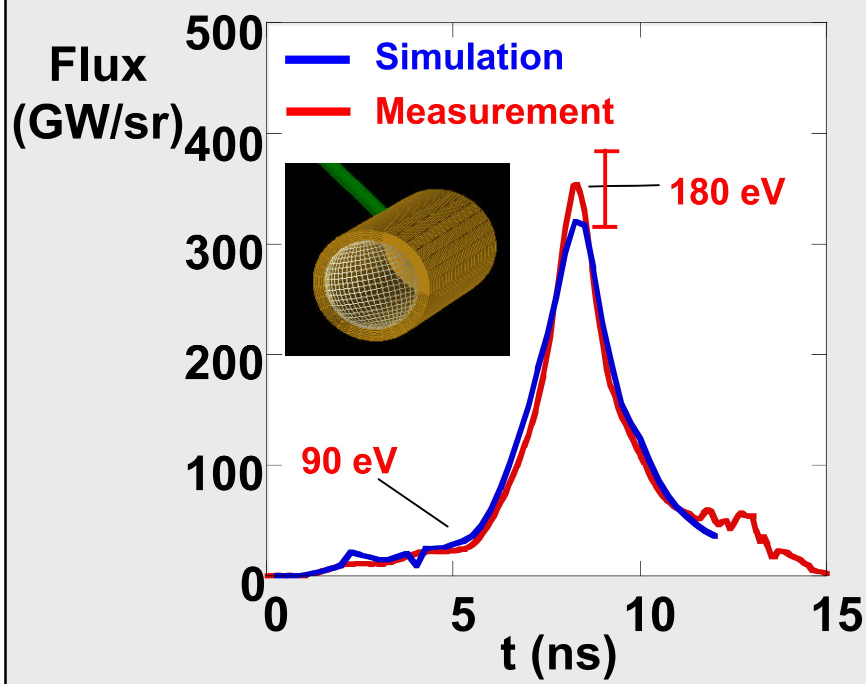
Incident, backcattered and calculated absorbed laser power



*SBS NBI time history assumed

Measured vs simulated flux including backscatter losses



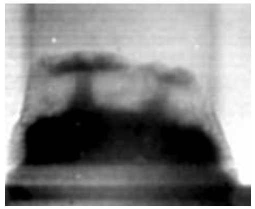
J. Kline et al., WO19.4

These hohlraums are testing our understanding and simulation capability of backscatter (e.g. what governs time-dependence and relative strength of SRS and SBS)?

J. Fernandez et al., TuO7.1

D. Hinkel et al., WPo13.1

Hydrodynamics



The first quad of NIF was used to both drive and backlight hydrodynamic jets of astrophysical interest

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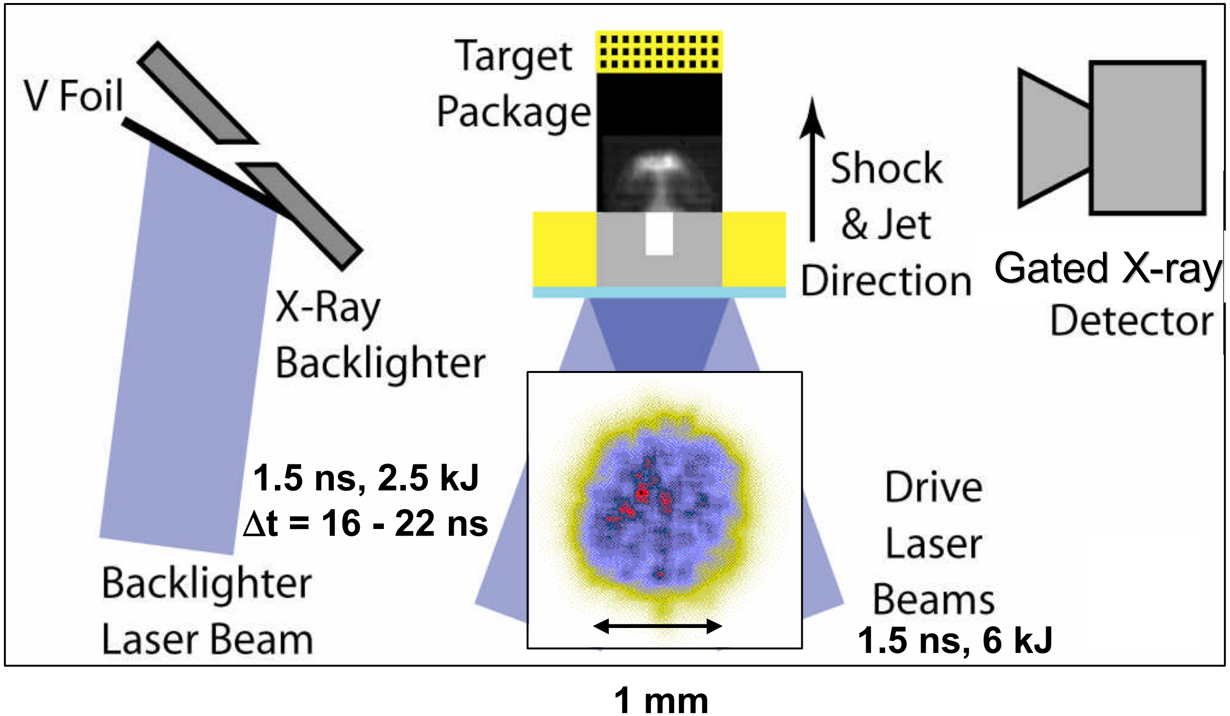
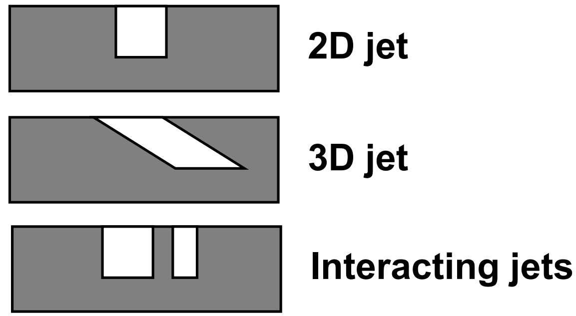


3 geometries compared

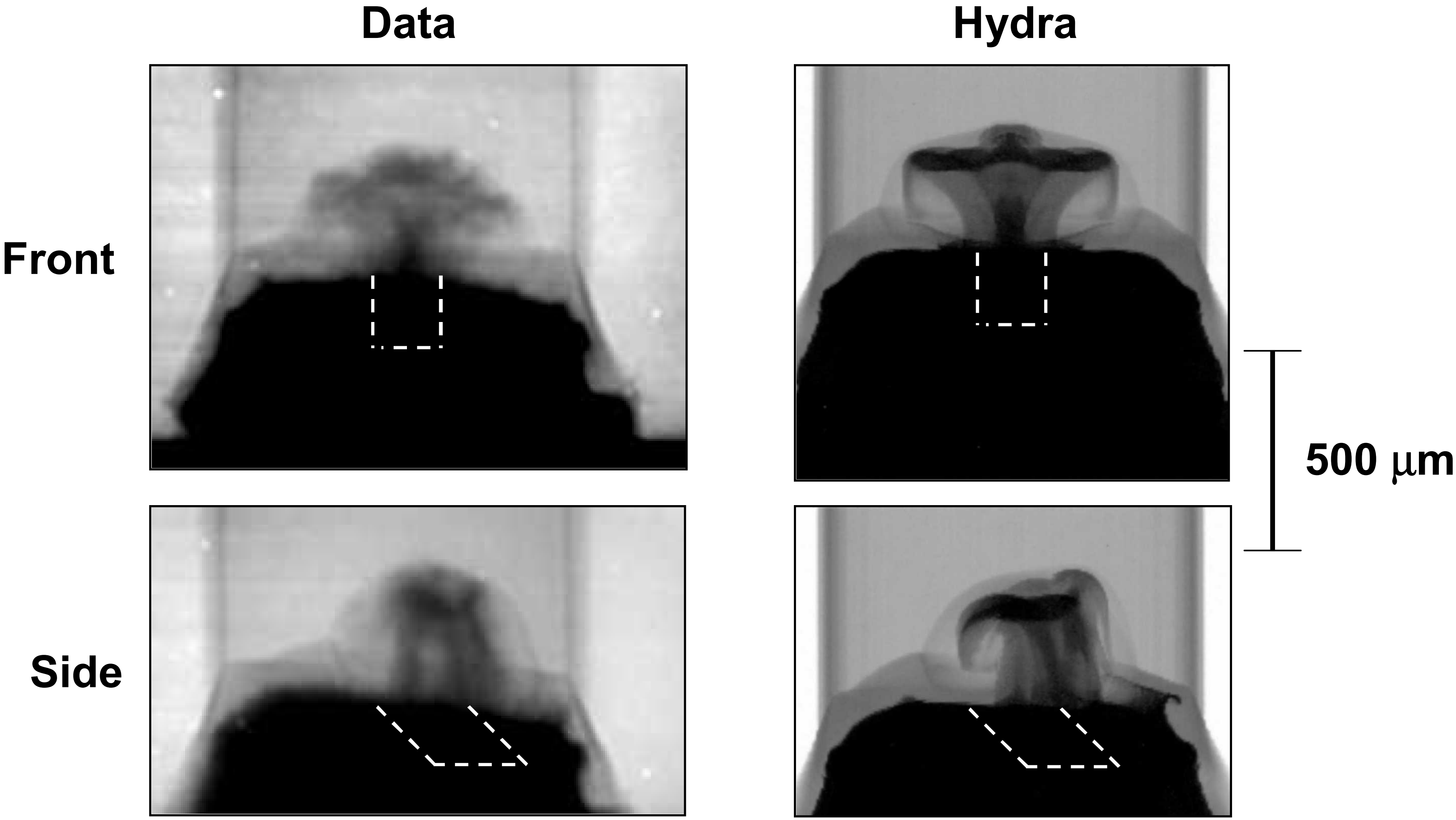


NIF met or exceeded experimental precision required

- Relative drive beam / target alignment to 60 μm rms, exceeding 100 μm required
- Shot-to-shot beam energy to 4% rms, exceeding 7% required
- Smooth, flat spatial profile over 500 μm as required

B. Blue et. al., MO2.1

To record the complicated flow, the 3D targets were imaged from orthogonal views



Data used to validate new generation of 3D codes

B. Blue et. al., Phys. Rev. Lett. 94 (2005) 095005

The flow structure in 3D targets was more complex but followed some of the 2D characteristics

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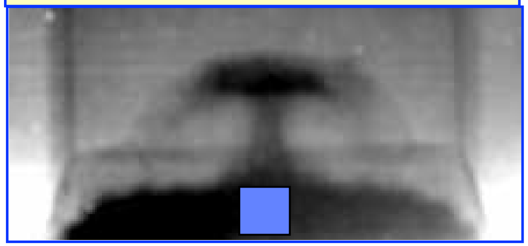
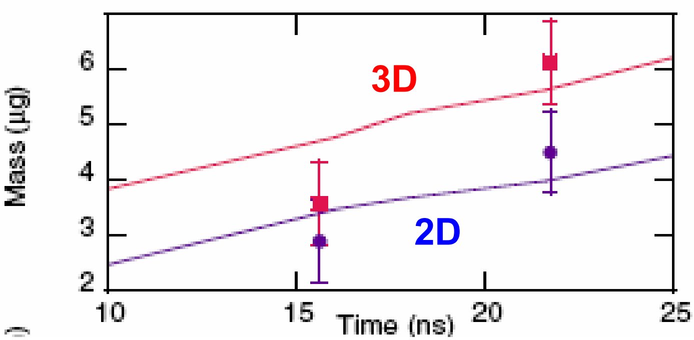
2D

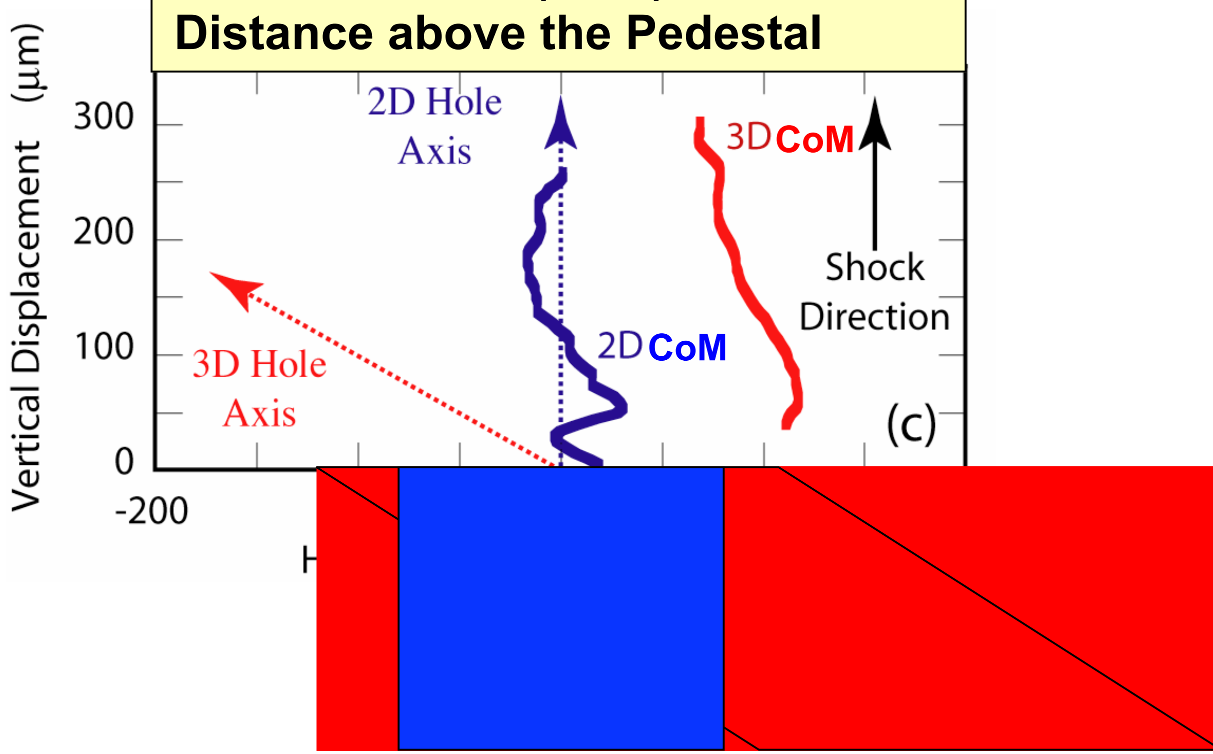


3D Asymmetric View



Mass ejected vs time agrees with simulations, proportional to hole "mass"

Center of Mass (CoM) vs Distance above the Pedestal



For both 2D and 3D:
Jet mass direction predominantly controlled by shock direction, not hole axis direction
Jet CoM controlled by average hole CoM, not exit center

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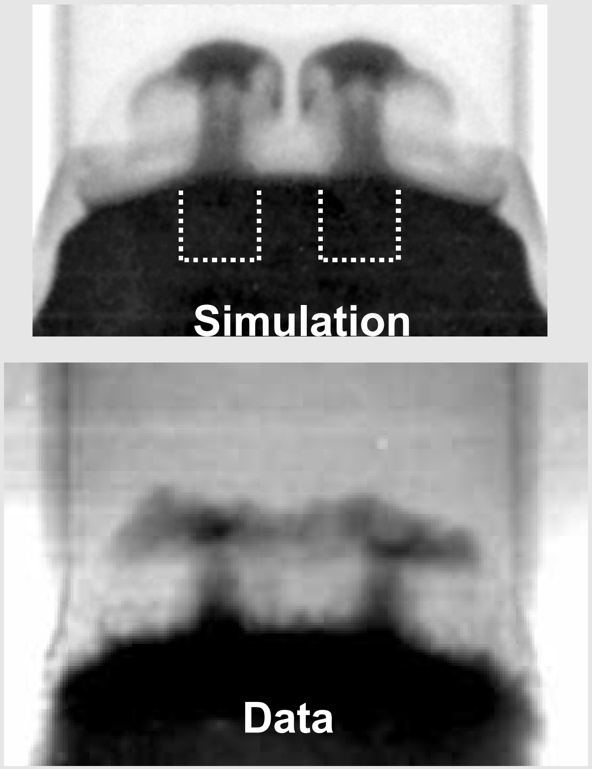
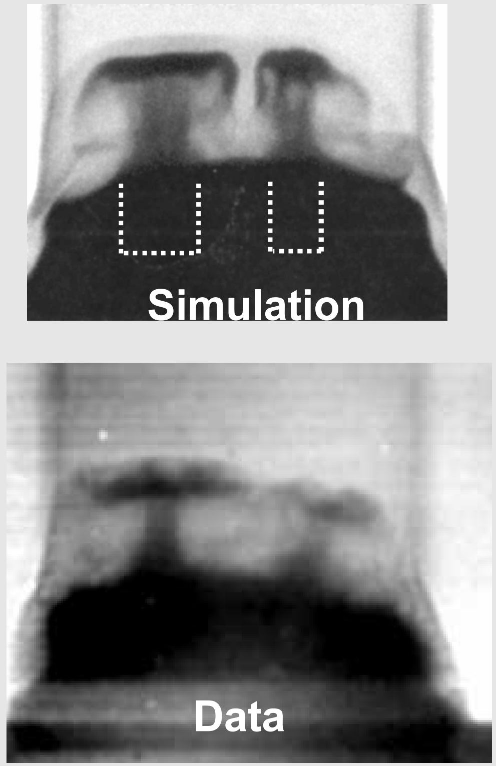
A dual jet experiment explored the physics of interacting jets

Equal Size Jets



Different Size Jets



Simulations predict no mixing between the jets, however the data suggests that they may

First quad NIF experiments successfully exercised all existing facility capabilities and delivered new results

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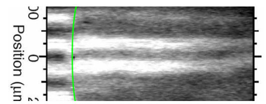
Diagnostics

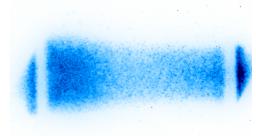
- Every type of optical and x-ray facility diagnostic successfully commissioned

Shock Propagation



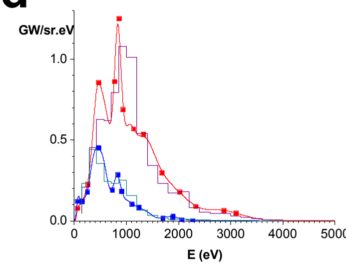
- Planar, steady long pulse direct-drive capability demonstrated

Laser-Plasma Interaction



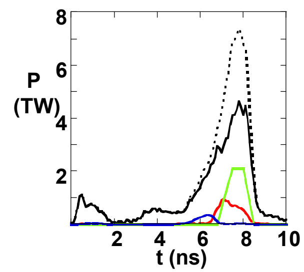
- Good laser propagation in long-scale length low Z plasma demonstrated, confirming understanding of filamentation threshold

Vacuum and Hot Hohlraums



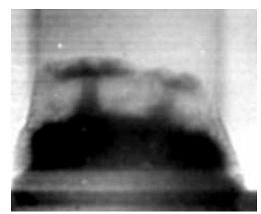
- Vacuum hohlraum performance agree with simulations and probe limits due to plasma filling

Gas-Filled Hohlraums



- High contrast shaped-pulse gas-filled hohlraum energetics help understanding of laser-plasma interactions

Hydrodynamics



- Study of hydrodynamic jet evolution extended to 3D and dual features

NIC Planning Status

The National Ignition Campaign

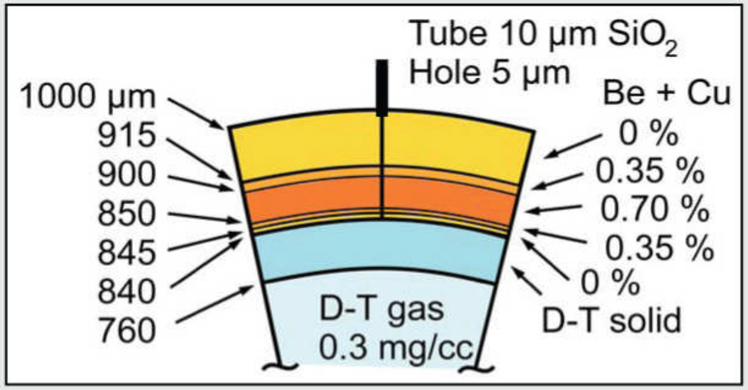
- Developed set of National Ignition Campaign objectives
- Agreed upon scope by participating sites (LLNL, LANL, LLE, SNL, GA)
- Developed self-consistent schedule with high-level milestones
- Preliminary budget allocation
- Developed a Campaign Execution Plan
- Structured organization for campaign execution

Approved by NNSA and is now operational

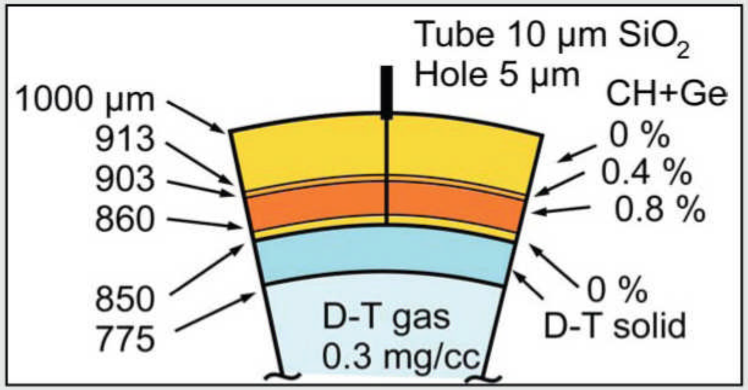
Improvements in ignition point designs have reduced laser energy estimates from 1.8 MJ to ~1 MJ

NIC
The National Ignition Campaign

Be Capsule



CH Capsule



	Be Capsule	CH Capsule
Yield	**13 MJ**	**10.4 MJ**
Eabs	**139 kJ**	**107 kJ**
Implosion velocity	**3.70 x 10^7 cm/s**	**3.86 x 10^7 cm/s**
Fuel mass	**0.161 mg**	**0.156 mg**
Ablator mass	**3.19 mg**	**1.76 mg**

Improve Performance

- **Cocktail hohlraums**
- **Laser entrance hole shields**
- **SSD, Polarization smoothing**

Improved Operability

- **Fill tubes for warm transport**

J. Lindl – MP1.1
S. Haan – Tu04.1
L. Sutter – Tu04.2


NIF is 80% complete

Process, assemble, and install over 5,700 line replaceable units (LRUs)

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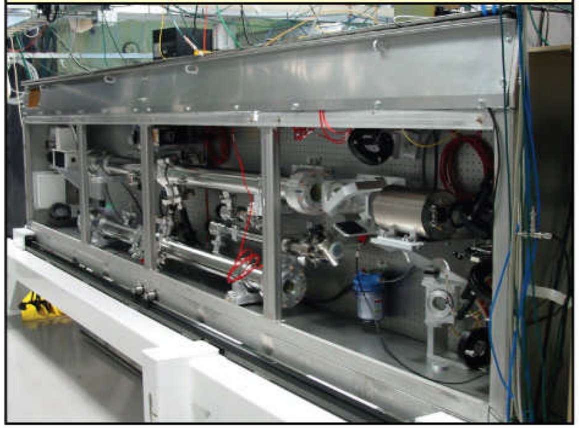
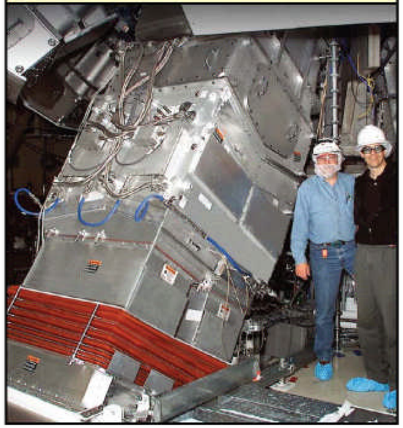
Preamplifier Modules (48)

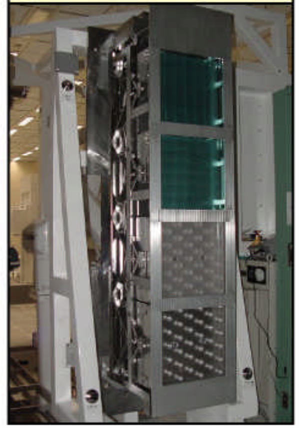


Laser Amplifiers (672)

Final Optics Assemblies (960)

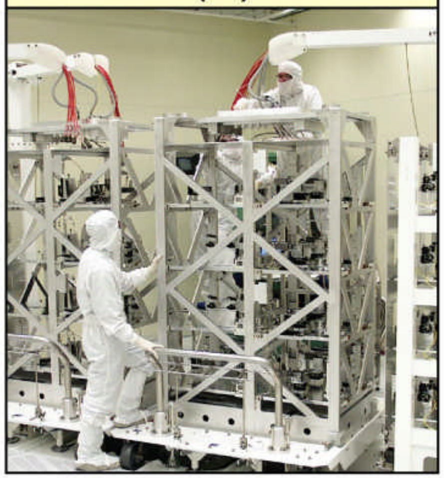


Laser Mirrors (656)



Spatial Filter Lenses (960)

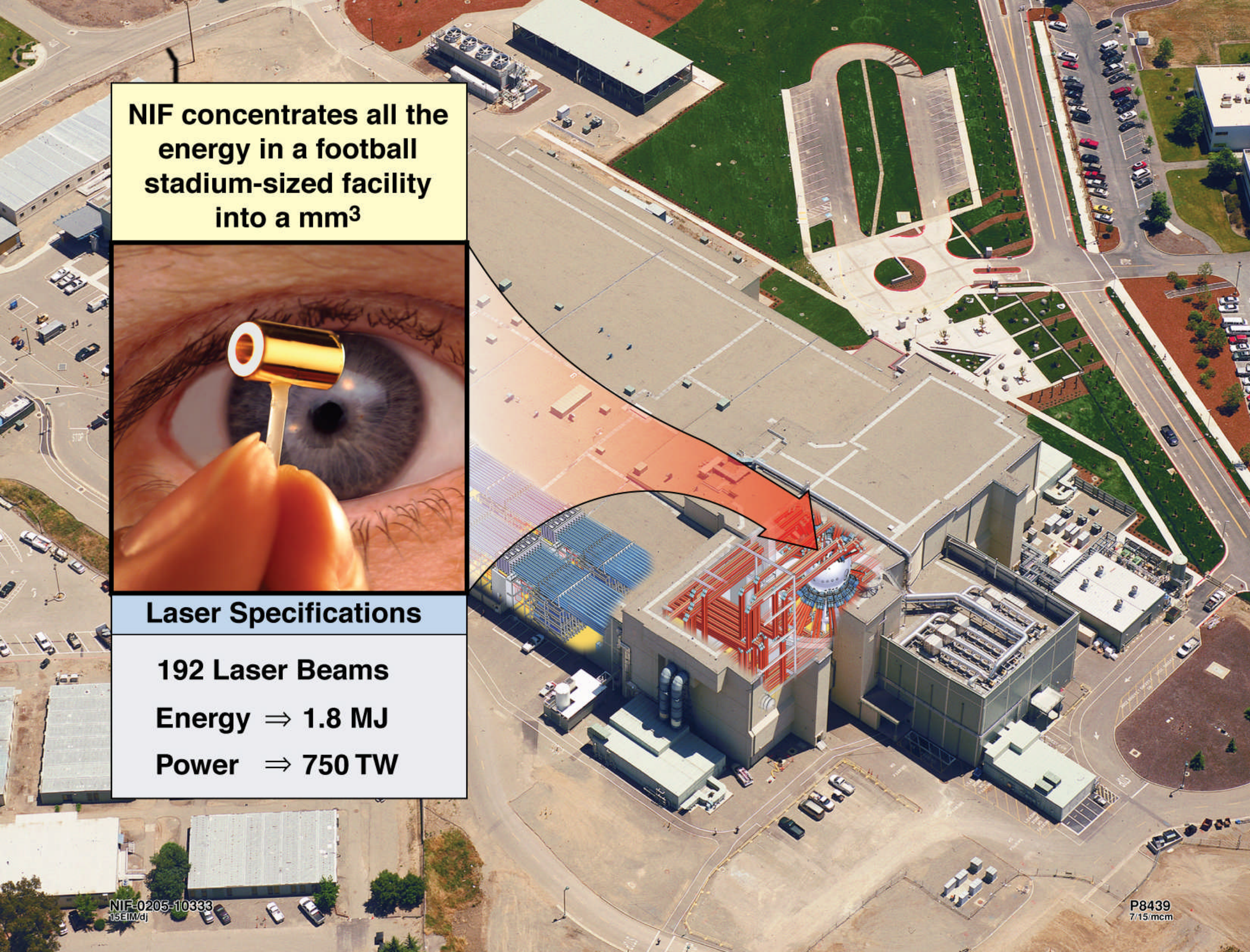
Spatial Filter Towers (72)

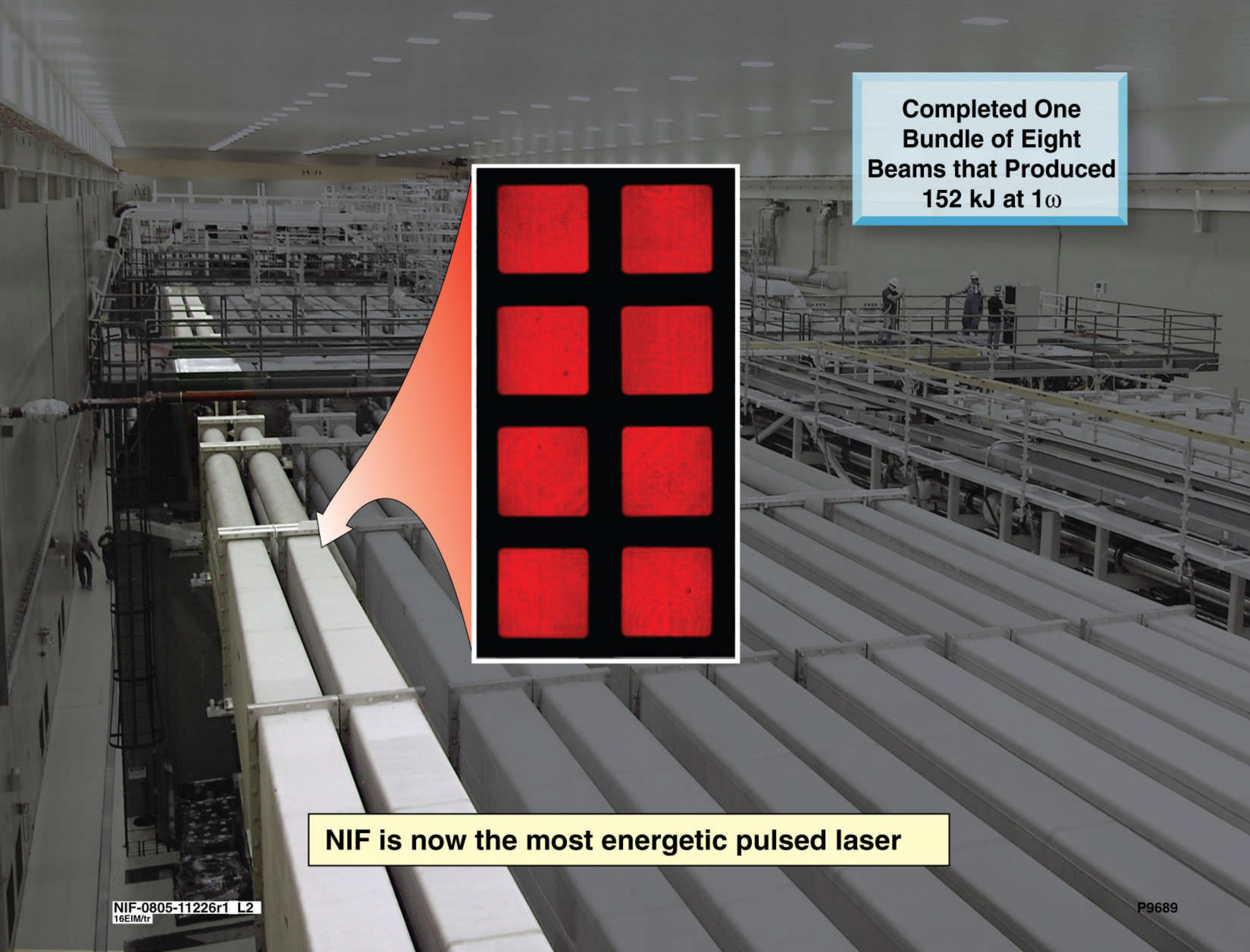


Plasma Electrode Pockels Cell (192)

Flashlamps (1008)

~900 LRUs installed to date


NIF concentrates all the energy in a football stadium-sized facility into a mm³
Laser Specifications
192 Laser Beams
Energy ⇒ 1.8 MJ
Power ⇒ 750 TW
NIF-0205-10333
15EIM/dj
P8439
7/15/mcm


Completed One Bundle of Eight Beams that Produced 152 kJ at 1ω
NIF is now the most energetic pulsed laser
NIF-0805-11226r1 L2
16EIM/tr
P9689

2ω and 3ω beamline energies are highest ever achieved

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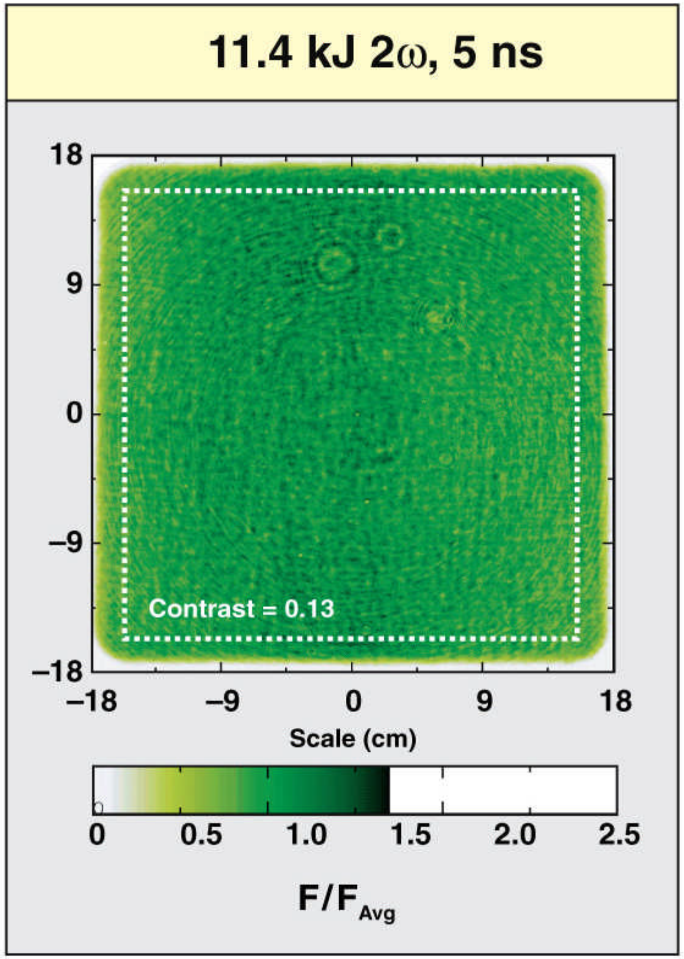

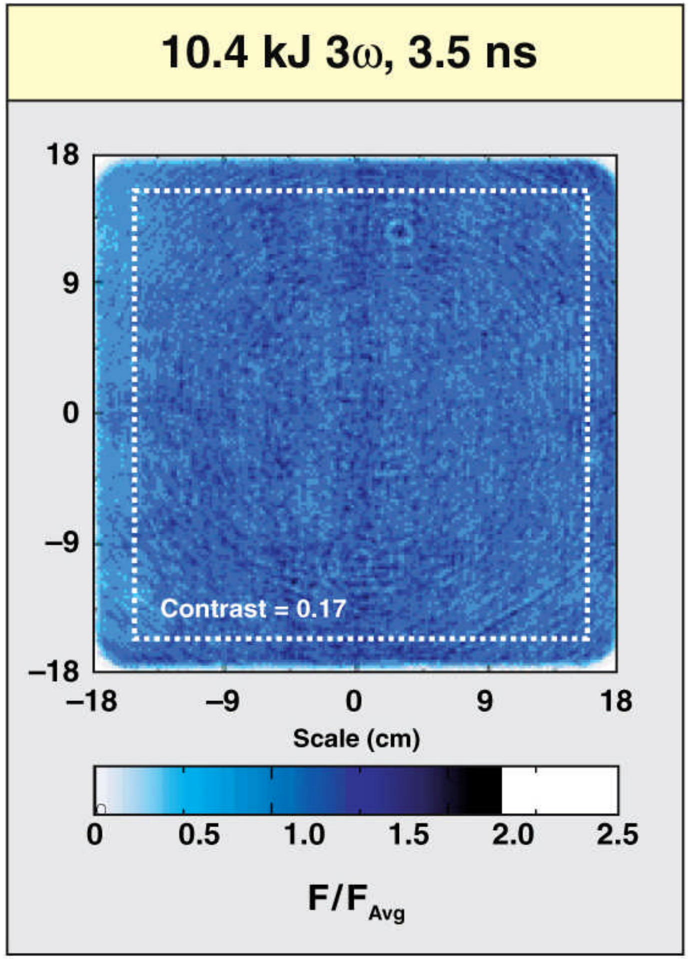

NIF Completion Criteria as well as Functional Requirements and Primary Criteria have been demonstrated on a single beamline at 3ω

A wide range of pulse shapes have been produced: Haan Ignition Pulse

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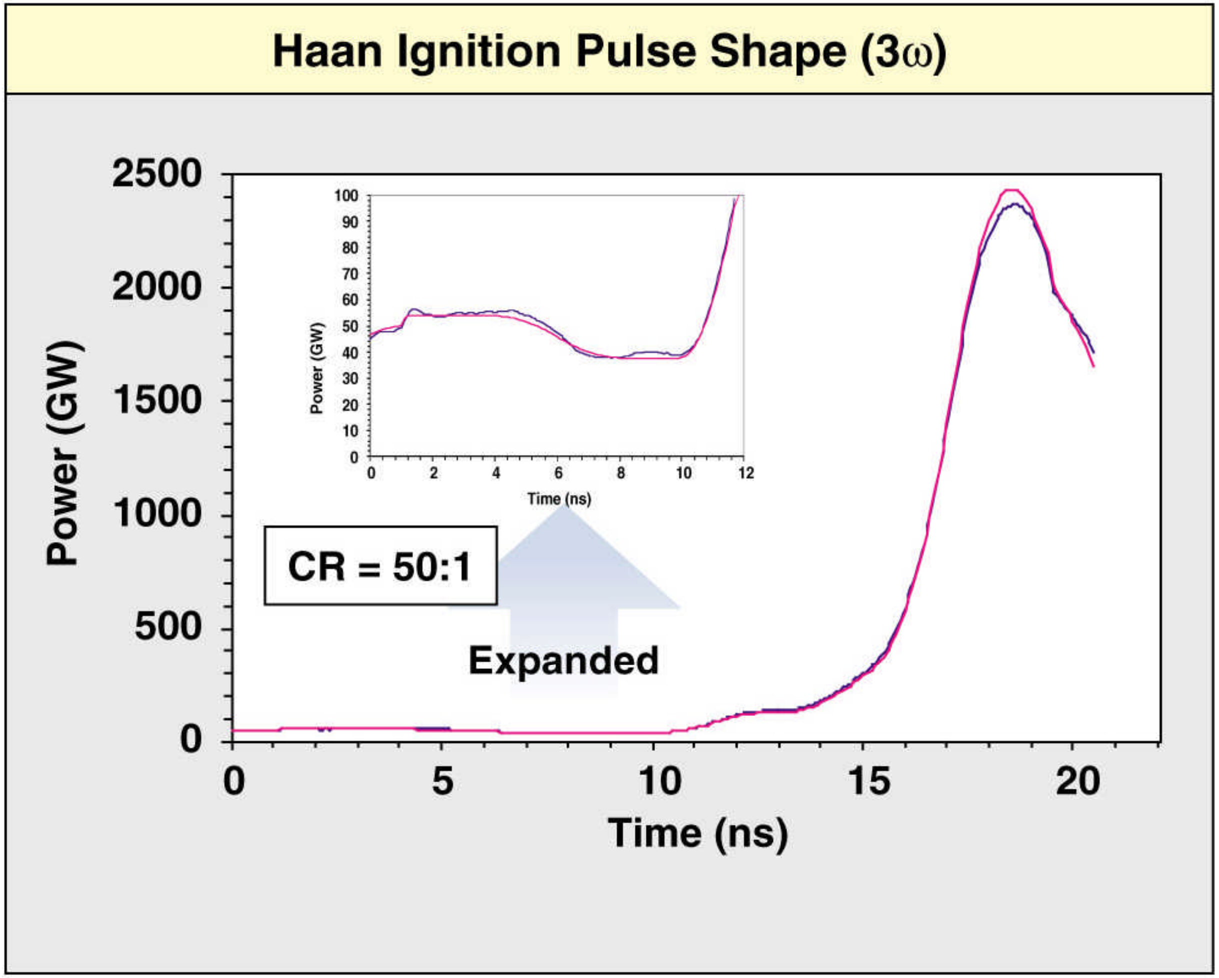

The complexities of the dual jet interaction challenge our modern hydronamics codes

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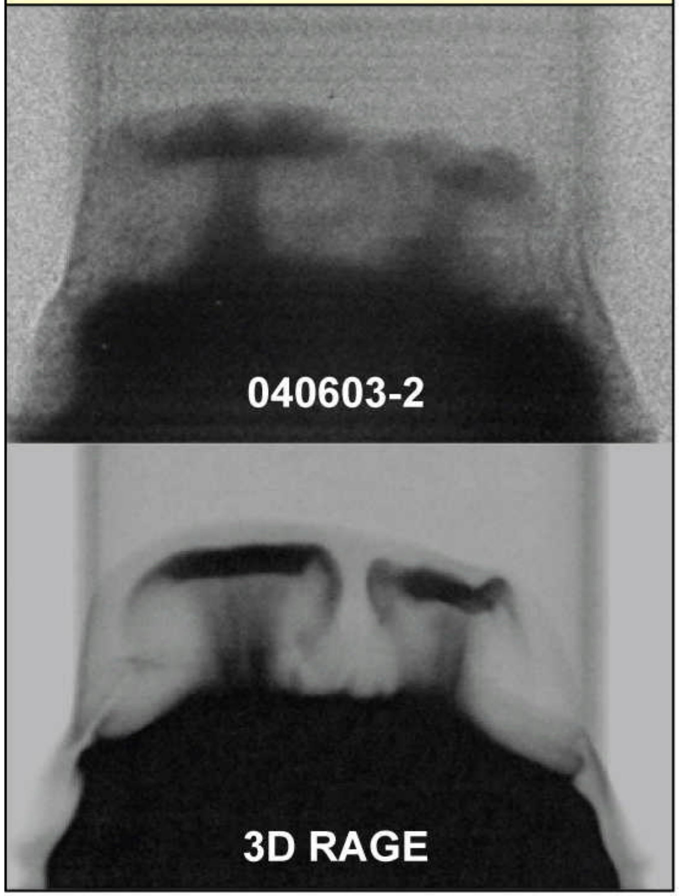
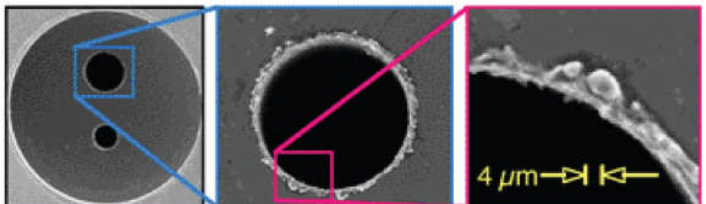
Asymmetrical Dual Jets



- As part of NIF Hydro Campaign, LANL conducted dual jet experiments
- 3D RAGE simulations show many quantitative similarities with data
- However, smaller-scale details are not fully captured
- This is attributed to small scale target defects that break symmetry early in the jet's evolution



Scanning Electron Microscope (SEM) images show μm-sized defects that break symmetry and seed small-scale mixing

Advanced Radiographic Capability is being developed for NIF

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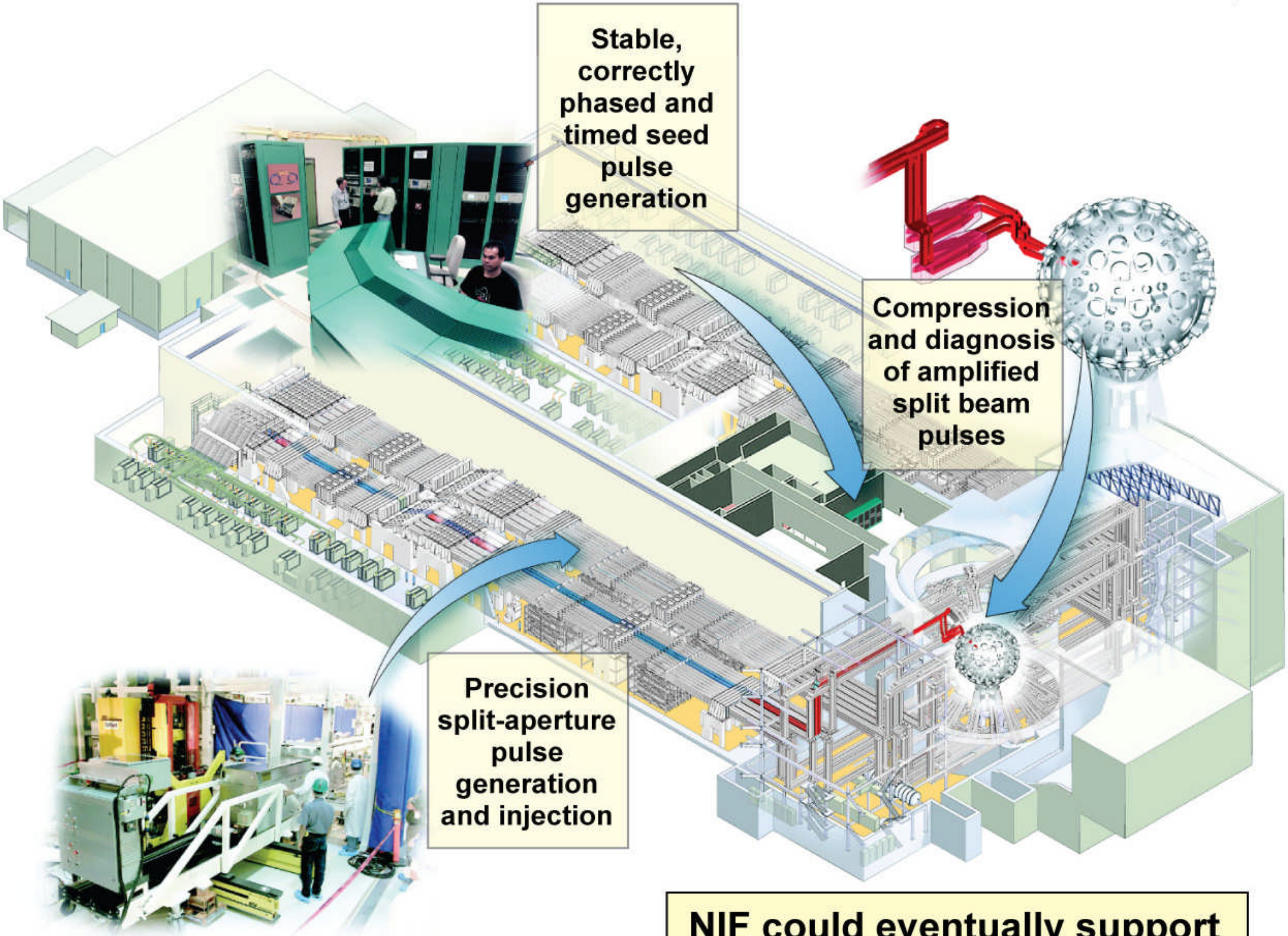
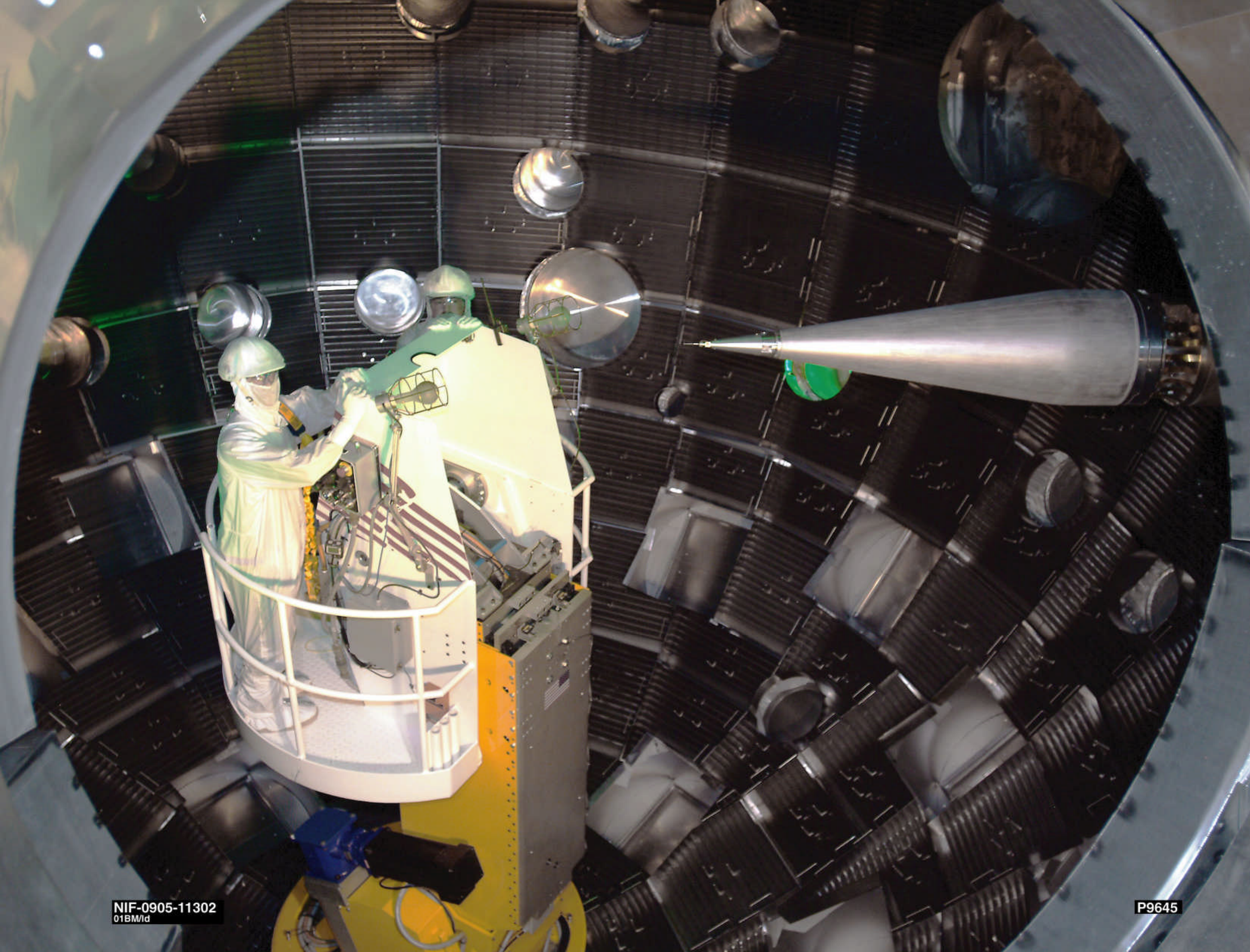


NIF could eventually support fast ignition capability


Target Chamber
17'6"
After
NIF-0903-07263DP#86L1
01EIM/ld
P6266


NIF-0905-11302
01BM/ld
P9645

NIF pointing requirement (<50 μm RMS) was demonstrated in June '04 Hydro Campaign

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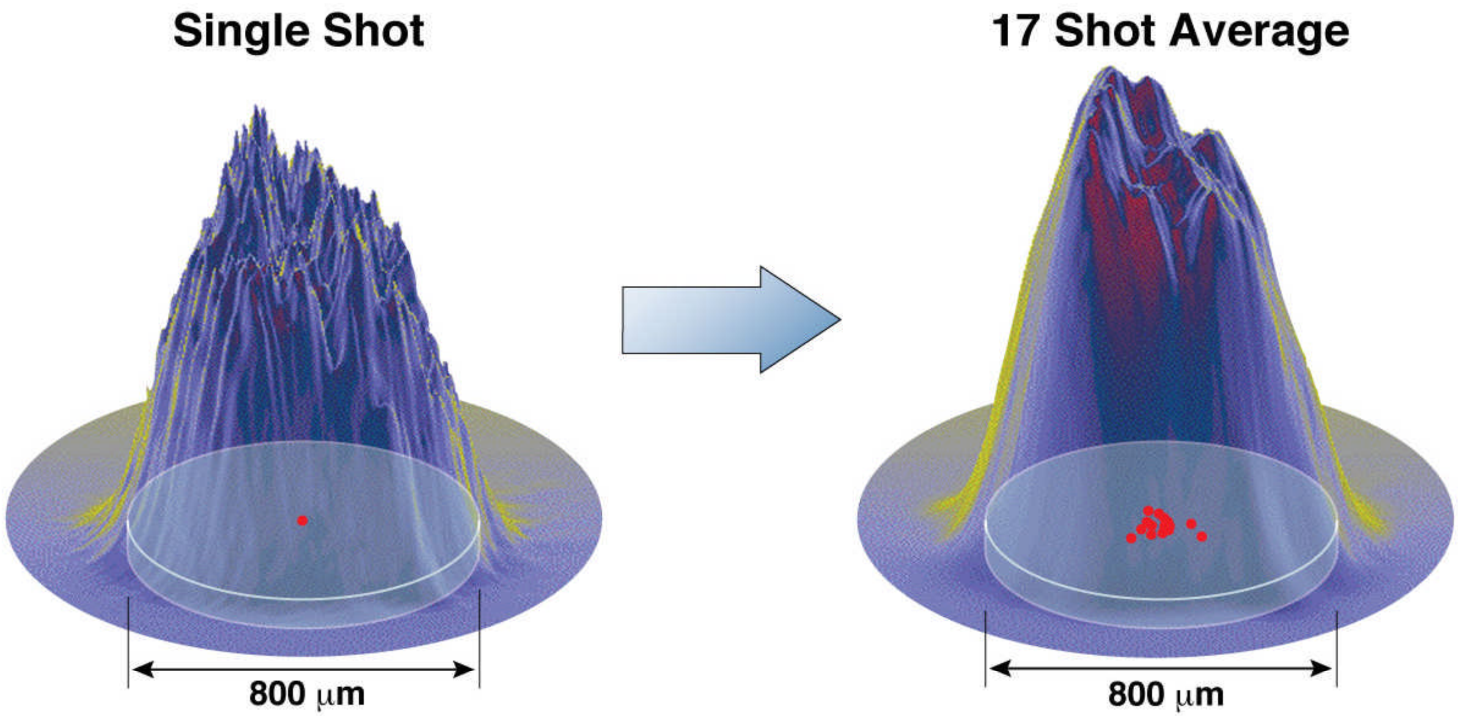

- 17 shot pointing deviation is 30 μm RMS
  - Better than NIF FR & PC pointing requirement of 50 μm RMS

NIF energy repeatability (<2% rms) supports power balance primary criteria

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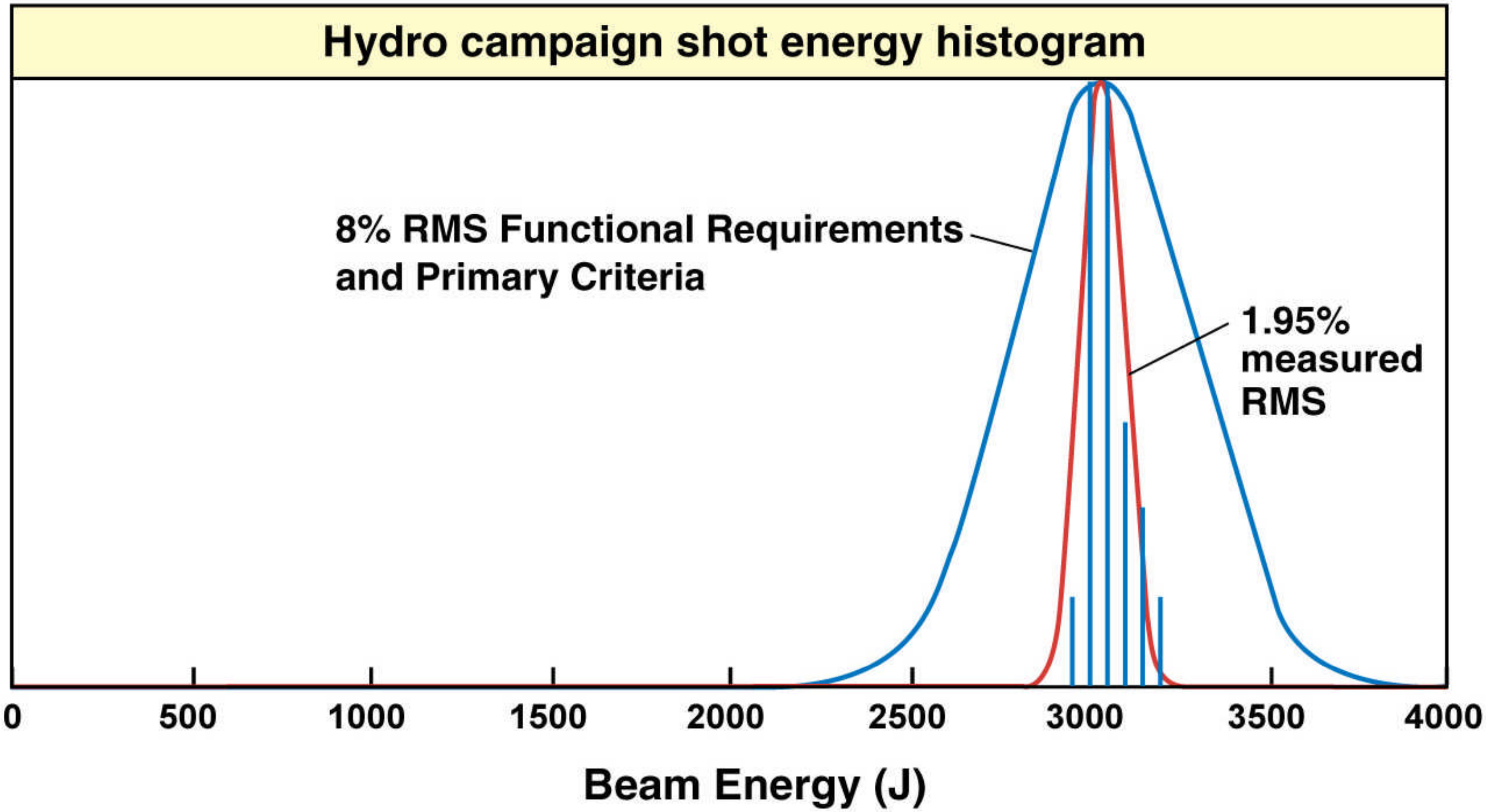

Measured RMS deviation of 1.95% is a small fraction of 8% power balance requirement